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EVALUATION OF ALTERNATIVE METHODS FOR FIRE RATING STRUCTURAL ELEMENTS

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Evaluation of Alternative Methods

for

Fire Rating Structural Elements

by

Kenneth R. Gilvary

Robert J. Dexter

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

A range of computational methods were evaluated for predicting the load capacity of structures subjected to fire. Results were compared to furnace experiments on loaded steel columns and concrete filled tubes. Simple calculations are accurate for simple cases such as steel columns at uniform temperature. Special-purpose finite-element software, SAFIR, was also accurate for members with nonuniform temperature distributions and/or composite cross-sections. SAFIR simulations of a continuous frame showed that it withstood three times the fire-exposure duration predicted from column furnace testing. Computational methods could serve as an alternative to the furnace test method for determining fire resistance ratings.

EXECUTIVE SUMMARY

Computational methods were evaluated for predicting the load capacity of structures subjected to fire. The purpose of the research was to evaluate the feasibility of using a computational approach to determine ASTM-E119 ratings as a possible alternative to full furnace testing. A range of possible approaches was evaluated, from simple calculations to sophisticated numerical simulation. Simple calculations were shown to be useful and accurate for most simple cases such as buckling of steel columns at uniform temperature. However, for members with nonuniform temperature distributions and/or composite cross-sections, special purpose computer programs are required.

Many of these programs have significant limitations, especially that they are not "user-friendly" and cannot be readily used by non-experts. Among the best is a program now called SAFIR which was developed primarily by J.M. Franssen at the University of Liége in cooperation with ARBED. SAFIR is easy to use and is useful for evaluating the fire resistance of all common types of construction.

The algorithms in SAFIR were validated by comparing the results for the buckling of isothermal steel columns to the results from commercial finite-element software. Initial applications of SAFIR involved simulating the response of structural elements under load as they are subjected to ASTM-E119 furnace fire tests. These applications included simulations of furnace experiments on loaded steel columns and

concrete filled tubes. Comparisons between results computed with SAFIR and measured experimental results show good agreement.

The usefulness of SAFIR was demonstrated by: 1) modelling complex structural elements that would be impractical to model with commercial finite-element software; and, 2) evaluating special situations such as partial fire exposure and exposure of a continuous frame to fire in one bay. It is concluded that SAFIR is a useful and reliable tool which could serve as an alternative to the ASTM-E119 furnace test method for determining fire resistance ratings. Acceptance of such a computational alternative could: 1) lead to significant savings in the cost of determining building-code-specified fire resistance ratings 2) provide increased fire safety; 3) result in more efficient, economical, and innovative building construction; and, 4) facilitate the use of advanced construction materials.

1.0 Introduction

Fire research can usually be associated with one of two main categories; life safety or structural integrity. Life safety research deals with issues such as smoke propagation, smoke alarms, sprinklers, fire walls, fire resistant materials, and safe effective exit paths. Structural integrity research deals with issues such as the load capacity a structural system during and after a fire. The primary focus of this report is the structural integrity of building structures subjected to fire.

Structural integrity research is very important to assure the safety of firemen that enter burning structures and people that are trapped inside burning structures. The potential hazard of damage to surrounding structures may also be of some significant concern. Finally, structural integrity research can help resolve issues concerning the reinstatement of fire-damaged structures.

The concept of fire-resistant design of structures has been developed since at least the late 1800's. The first set of standardized column fire tests was carried out by Underwriters Laboratories, Inc. in 1917. The results from those tests indicate that most steel columns collapse under full design load at average temperatures above 538°C [1].

Design for fire resistance of steel frames is still based, for the most part, on the empirical concept of limiting the surface temperature of members to 538°C. For various reasons that are explained in the following section, this approach is inefficient and does not accurately predict structural integrity. An alternative numerical approach is investigated herein. The approach involves simulating the thermal and mechanical behavior of a structure subjected to prescribed temperature histories on the surfaces of particular members using the finite-element method.

The determination of an appropriate temperature history is not addressed in this report. Rather, this preliminary research is focused on the behavior of structural members exposed to an accepted "standard fire" temperature history. As explained in the following section, this standard fire history is excessively conservative. Research is being conducted to determine rational temperature histories based on the contents and configuration of a building and various fire scenarios. These rational histories could also be used with the numerical approach evaluated herein in lieu of the standard fire temperature history.

The numerical approach is particularly useful for modelling the behavior of complex members, non-isothermal members, members only partially exposed to fire, and continuous frames. An example of an innovative nonconventional frame is the exposed steel frame shown if Figure 1.0.1 below.

Exposed Steel Frame with Water-Filled Columns

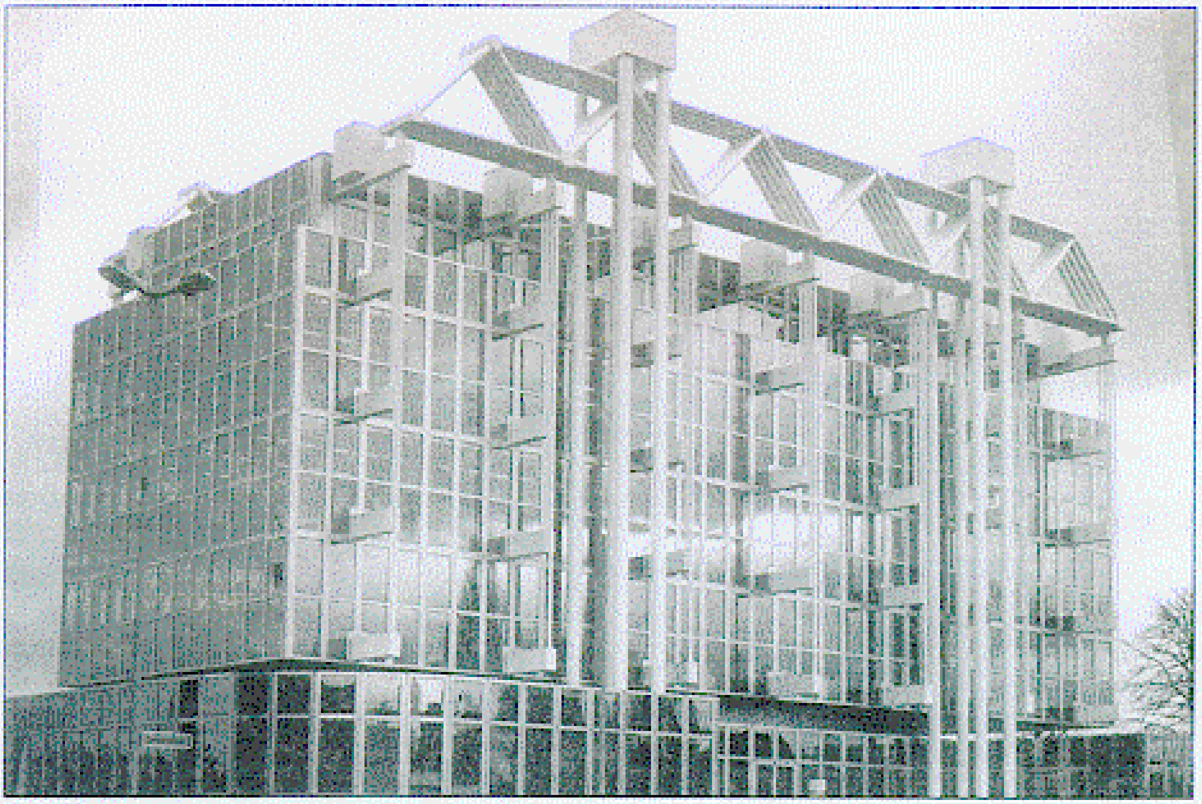


Figure 1.0.1 - Norcon Building in Hannover Germany [2].

Exposed steel frames such as these are becoming increasingly more common in many parts of the world. It is clear that the steel columns shown above could not be surrounded by fire, but, the present codes in the U.S. require that columns such as these, be tested with fire exposure on all four sides. Unprotected columns cannot pass this test, therefore exposed exterior frames typically do not meet building code requirements. An extensive special analysis and receptive building officials are presently required to allow the construction of a building such as this in the U.S.

Another significant potential use of a numerical approach is to study the issue of reuse of a structure after a fire. Dispute over the adequacy of structural members can be very costly. The Meridian Plaza building in Philadelphia, shown in Figure 1.0.2 below, is a good example of this.

Meridian Plaza (Five years after Fire)

Figure 1.0.2

The Meridian Plaza is a 38 story office tower which stands directly across from city hall in downtown Philadelphia. In February 1991, a fire started on the 22nd floor and burned through to the 30th floor. The building is presently covered with plywood and is an eye-soar to passing tourists and a detriment to surrounding businesses. A recent article in the Wall Street Journal [3] described the building as "a high rise crack house". The building is still in this condition because of protracted litigation over the extent of the repairs required to reinstate the building.

One of the biggest issues is the extent of repairs necessary to restore the load capacity of the frame of the building. The owners of the building contend that the fire created residual stresses which weakened the load capacity of the building. The owners want the fire damaged top of the building to be replaced from the 19th story up. The insurance company and its engineers contend that the frame of the building is safe, and that only excessively deformed beams need to be replaced. The owner's option would cost 400 million dollars, but the insurance company's option would only cost 100 million dollars. The two parties are finally coming to some agreement after more than six years [4,3]. An accepted numerical method for the assessment of the capacity of buildings exposed to fire could have hastened the resolution of this dispute.

The purpose of this report is to present an evaluation of a range of methods for the prediction of the thermal and mechanical response of structures subjected to elevated temperatures. In addition, the accuracy and usefulness of a special-purpose finite element program called SAFIR is evaluated.

The following section contains background about the current approach used to design for fire resistance, available experimental data, and various computational approaches for modeling structures exposed to fire. Chapter Three contains a detailed description of the finite-element software SAFIR. Various applications of SAFIR are presented in Chapter Four, including comparisons to experimental data. Chapter Five discusses a hand calculation that can be used for simple cases. Chapter Six has some discussion, followed by some conclusions and recommendations for future work.

2.0 Background

2.1 Current Approach

In the United States, fire resistance requirements specified in building codes are typically expressed in terms of fire endurance ratings of a building's structural members. The ratings are determined according to the American Society for Testing and Materials (ASTM) E119 test method "Standard Methods of Fire Test of Building Construction and Materials" [5]. An ASTM-E119 rating is defined as the length of time a member of a structure can withstand exposure to the standard fire without critical loss of its load-bearing capability. The standard fire is defined in the ASTM-E119 document in terms of a specified temperature-time history.

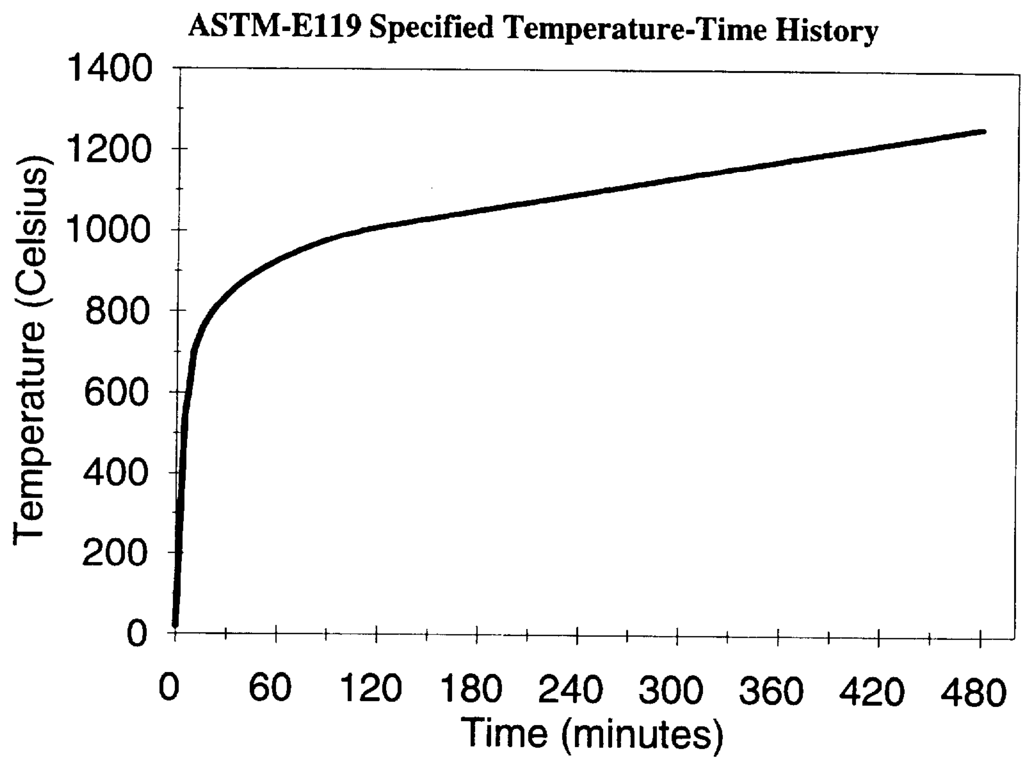


Figure 2.1.1 [5]

Structural elements are rated according to ASTM-E119 by testing them in a furnace, where they are exposed to the standard fire environment shown above. It is difficult for a furnace to follow the ASTM-E119 temperature-time curve exactly, therefore; the code allows for some variation from the prescribed curve. This is one of many reasons which can contribute to scatter in results from test to test.

For structural columns, solid structural steel beams and girders, ASTM-E119 provides two rating options, namely, furnace testing with or without simultaneous load. All other structural (i.e., load-bearing) building elements are always rated under loaded conditions [5].

In the case of testing without load, the ASTM-E119 acceptance criterion for rating a structural element is that the temperature of the steel does not exceed certain specified values. The limiting average exterior temperature of a structural steel column or beam is 538°C, which was probably chosen because it is both: 1) equivalent to the nice round 1000°F; and, 2) an approximation of the temperature at failure of hot-rolled structural steel and prestressing strands in furnace tests under typical allowable service loads.

Regardless of whether the test is carried out with or without load, a column is exposed to the standard fire on all four sides. This type of exposure is excessively severe for exterior columns, especially in an exposed exterior frame. Also columns in rooms with virtually no combustible material such as a swimming pool should not be required to withstand such a severe fire load.

Figure 2.1.2 shows a concrete filled tube still in place at the end of a loaded ASTM-

E119 furnace test. There are presently no furnace test facilities, such as this, in the U.S. which are capable of carrying out column tests under load. For this reason, all ASTM-E119 column ratings determined in the U.S. follow the no-load option. Some structural steel column ratings under load have been acquired at the laboratories of the National Research Council of Canada [6], which has the only loaded-column furnace facility in North America.

Concrete Filled Tube After ASTM-E119 Furnace Test

Loaded Option

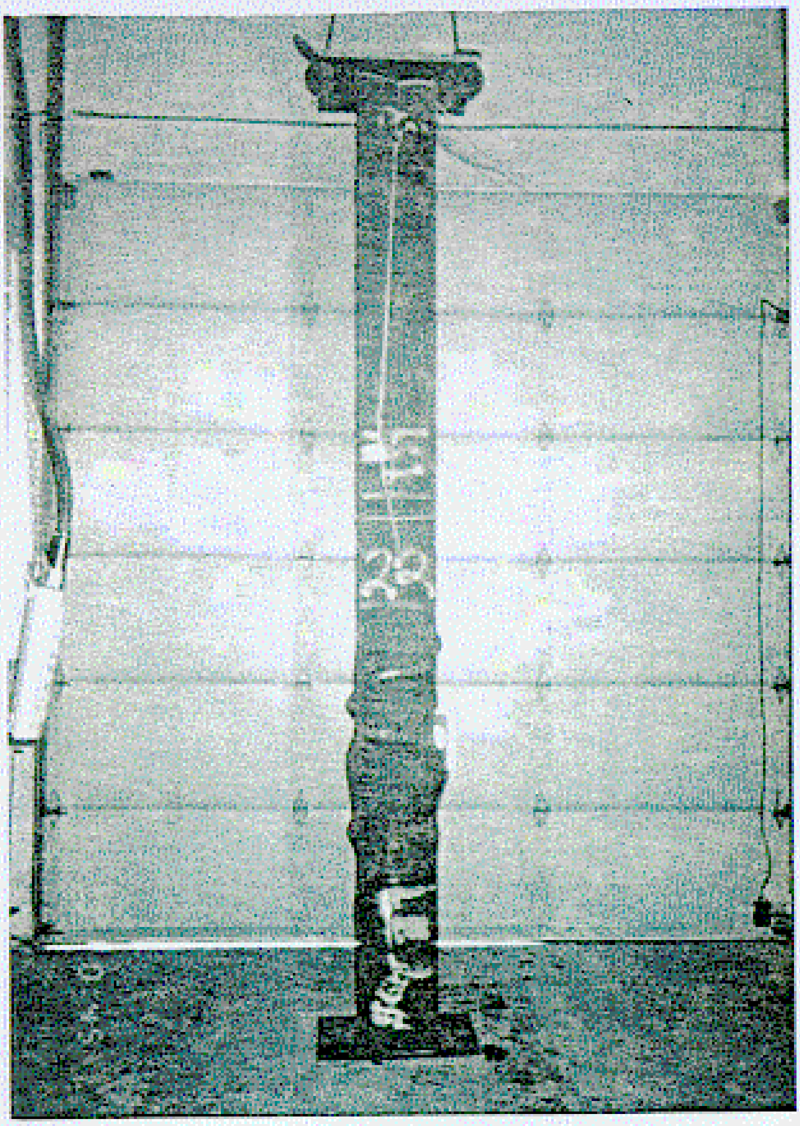


Figure 2.1.2 [7]

The ASTM-E119 acceptance criterion for a column under load is that the column successfully sustains the applied load for the duration of the test. No temperature-limit criteria are involved. The alternate test for steel columns can be applied to bare steel columns or steel columns protected with some type of fire resistant covering, provided that protection is not required, by design, to function structurally in resisting applied loads [5]. In the case of composite columns, such as a steel column incased in concrete, a significant amount of the load may be taken by the concrete. There are no provisions in the code for testing composite columns without load. Therefore, the numerical approach could be particularly useful for modelling composite columns.

ASTM-E119 requires that the average temperature of a member be measured by thermocouples, placed on the outside surface of the structural steel column or beam. This is necessary because it is impractical to measure the temperature of the inner material. It is clear that this would be a conservative measurement, considering that the outermost surface, which is exposed to the fire, will always be the hottest part of the cross-section [8]. A computer simulation can clearly and accurately show the temperature distribution throughout a cross-section as a function of time.

Besides the technological differences between the two test options, there are other more general problems with the rating procedure. Although ASTM-E119 ratings are very conservative, these ratings have been used successfully for many decades as the basis for fire-safe design in U.S. In fact, where required rating criteria of building codes have been satisfied, cases of partial collapse are few and cases of complete collapse of large multistory buildings are non-existent.

The primary problem with the ASTM-E119 rating is that the standard fire does not accurately simulate real building fires [8]. For example, the temperature of the standard fire is monotonically increasing with time for up to eight hours. This temperature history was originally recorded from a fire that was continuously fueled with railroad ties [9]. The temperature of a real fire rises to a peak value and then begins to decrease with time. A floor in a typical office building will generally burn itself out in about two hours. It is generally accepted that the continuously increasing ASTM-E119 temperature history would be impossible unless the fire was being continuously fueled.

Fire severity as well as the peak temperature and time to the peak of the temperature-history depend on several factors, including;

1. Fire load (amount and type)
2. Distribution of this fire load
3. Specific surface characteristics of the fire load
4. Ventilation
5. Geometry of the fire compartment
6. Thermal characteristics of the enclosure boundaries
7. Relative humidity of the atmosphere [5]

The European building code uses a similar temperature-time history to the ASTM-E119 standard fire, referred to as the ISO temperature-time history. A comparison between the ASTM-E119 and the ISO curve is shown below. The term "fire resistance" is defined herein as the duration of exposure to one of these standard fires of a loaded structural element [10,11].

ASTM-E119 and ISO Temperature-Time History

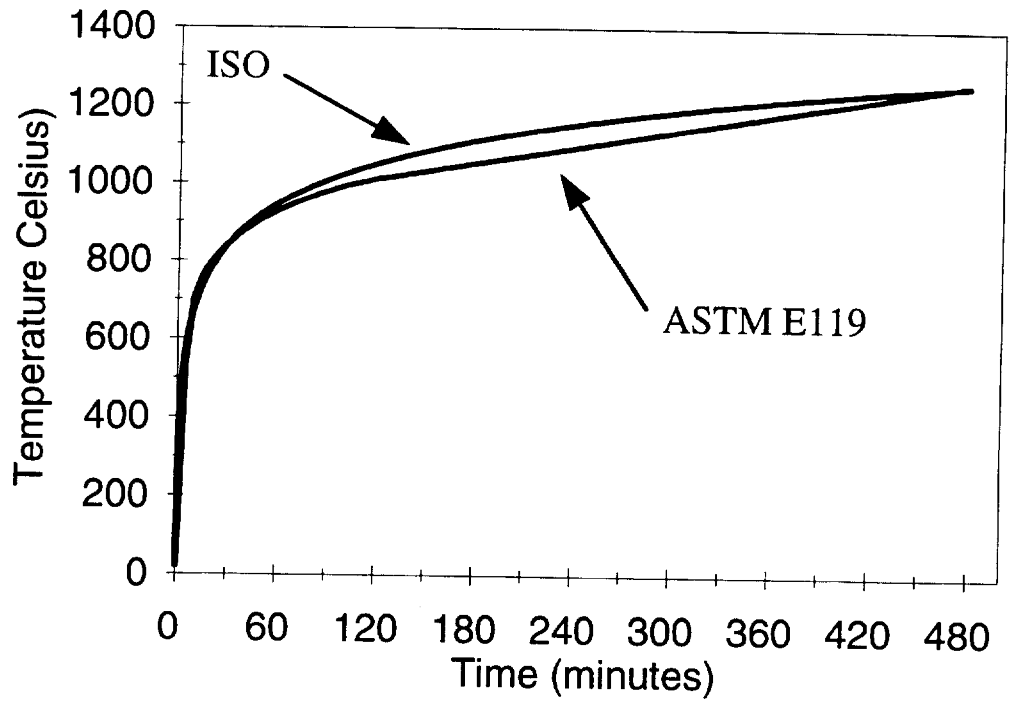


Figure 2.1.3

Figures 2.1.4 and 2.1.5 show photographs of a furnace test being conducted at CTICM in France on a "slim floor" system, used in many parts of Europe. This test is similar to the ASTM-E119 test for floor systems. The slightly different ISO standard fire temperature history was used.

Furnace Test on Slim Floor System

Top View

Figure 2.1.4 [12]

Furnace Test on Slim Floor System

Bottom View

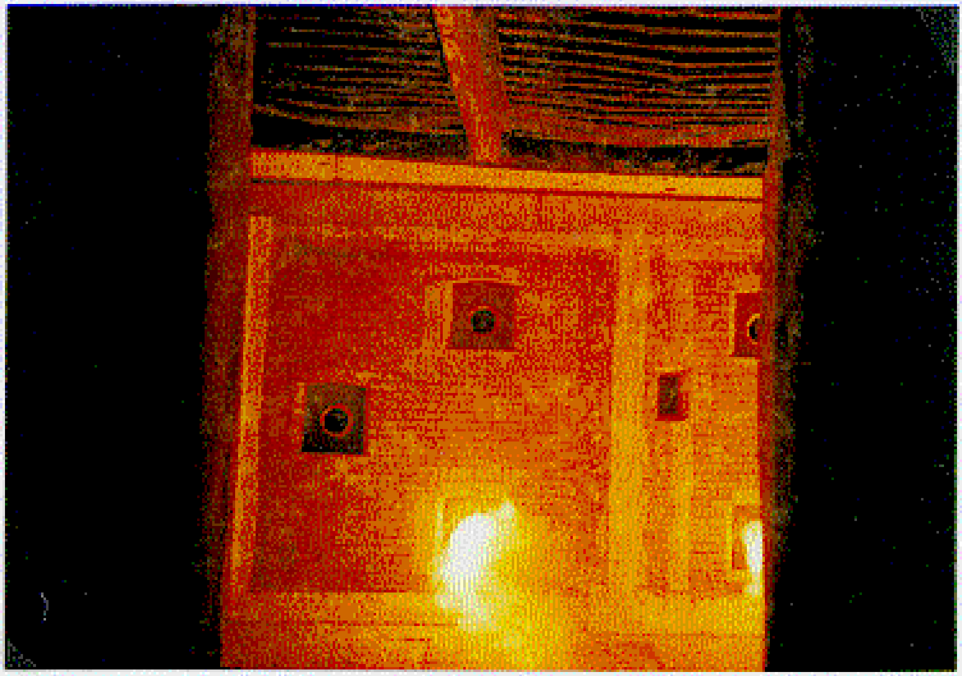


Figure 2.1.5 [12]

The standard fire is so severe that the fire brick still glows brightly, even 20 minutes after the burners are turned off.

Close examination of the above photos reveal considerable deflection, but this loaded floor system withstood the standard fire for over three hours without any fire protection at all. The good fire resistance of the floor system in this test is partly due to the negative moment and membrane action that develops, due to continuity of the floor system over the walls of the test furnace. This floor system test is used as an example to illustrate that the load capacity of an individual structural element exposed to fire is dependent on the end constraints, which are coupled to the response of the overall structure. The effect of end constraints on fire endurance of steel framed construction is discussed in a recent paper published by AISC [13]. This paper shows that a beam with rotation and displacement end restraints has greater fire resistance than unrestrained beams.

A simple frame analysis using the SAFIR software is discussed in Chapter Four. This frame analysis also demonstrates the additional fire resistance provided by a continuous structural system relative to single member behavior. Because of the limited size of test furnaces, in most cases only small assemblies or sub-assemblies can be tested. An engineer must try to combine results from several tests to predict how a structure will perform in an actual fire. Without a frame analysis simulating a fire scenario, end constraints of structural columns in a fire must be assumed. Such constraints are generally not simple and not constant in time. Steel plates or reinforced concrete can be used to represent the boundary conditions in a column furnace test. In many cases these boundary conditions can also act as a heat sink which lowers the average temperature near the end of the column, which can confound the results.

Another criticism of furnace testing involves the steam released from concrete assemblies. The furnaces are typically not well ventilated and the steam is confined to the small volume of the furnace. The steam can have a significant effect on the heat flux through the air surrounding a concrete column. The thermocouples used to monitor the temperature of the test fire are required to be set 12 inches from the specimen. The thermocouples are located at the ends of the poles positioned on either side of the test specimen in Figure 2.1.2.

Another conservative aspect of the ASTM-E119 ratings is that it treats all structural elements as if they were loaded to their maximum service load as required in the furnace test. Typically, columns and many beams are sized larger than required for service load capacity in order to control lateral drift [14]. However, regardless of the expected level to which individual elements are actually loaded, present building codes would typically require like structural elements to have the same ASTM-E119 rating regardless of their actual loading.

It is clear that computational thermal and structural analysis can provide a means of addressing and resolving these problems with furnace testing according to ASTM-E119. A computer model can be used to simulate the results of fire tests without the excessive cost of time and materials. The stability of a building can only be practically assessed using numerical methods [15]. A computer model can quickly and easily simulate different fire loads and structural loads. Results from a numerical simulation include temperatures, deflections, stresses, strains and total structural response.

2.2 Available Experimental Data

According to ASTM-E119, no comprehensive test program has been conducted to develop data on which to derive statistical measures of repeatability (within-laboratory variability) and reproducibility (among-laboratory variability) of experimental fire test results [5]. With this in mind, data were collected from labs in Europe, Canada, and Australia. It was observed that there was considerable variation in the data for like structural members, even when tested under the same conditions. The variation among replicate tests of steel columns was as high as 27.4%, and the variation for replicate tests of concrete columns was as high as 39.5%.

There is one particular set of tests from Rennes, France where there were enough data from tests on the same size section, at different loads to create a reasonable basis for comparison to computer simulations and hand calculations. The section used in these tests was the rather small European H-section, HEA-100.

Furnace Test Data

HEA-100

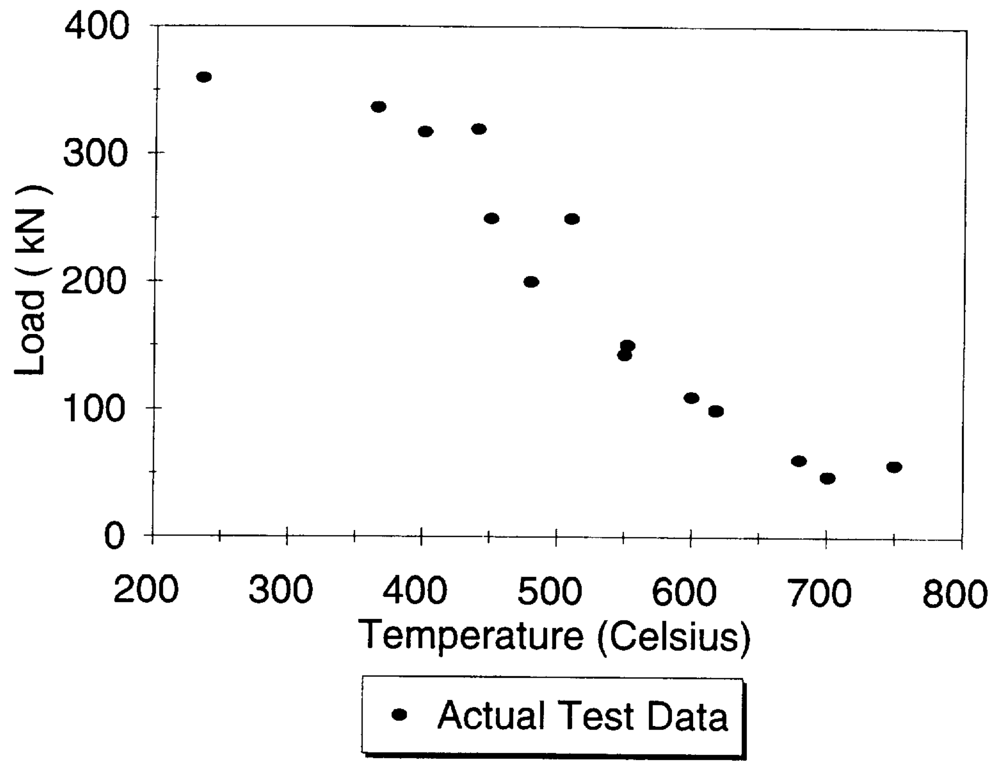


Figure 2.2.1

2.3 Computational Approaches

Various computational approaches for the evaluation of fire resistance exist. Many of these are used routinely outside the United States. These approaches range from simple hand calculations to complex nonlinear numerical simulation techniques. An example of a simple hand-calculation approach can be found in the Australian building code [16]. In this approach, structural elements are checked to see at what temperature they would fail given specified loads. Equations for the structural material properties are similar to those normally used for loading at ambient temperatures, except that temperature-dependent material properties are specified. Fire protection is provided only as necessary to prevent the element from reaching the limiting temperature for a specified time. Although relatively simple, this approach solves the problem of all like elements requiring the same fire protection.

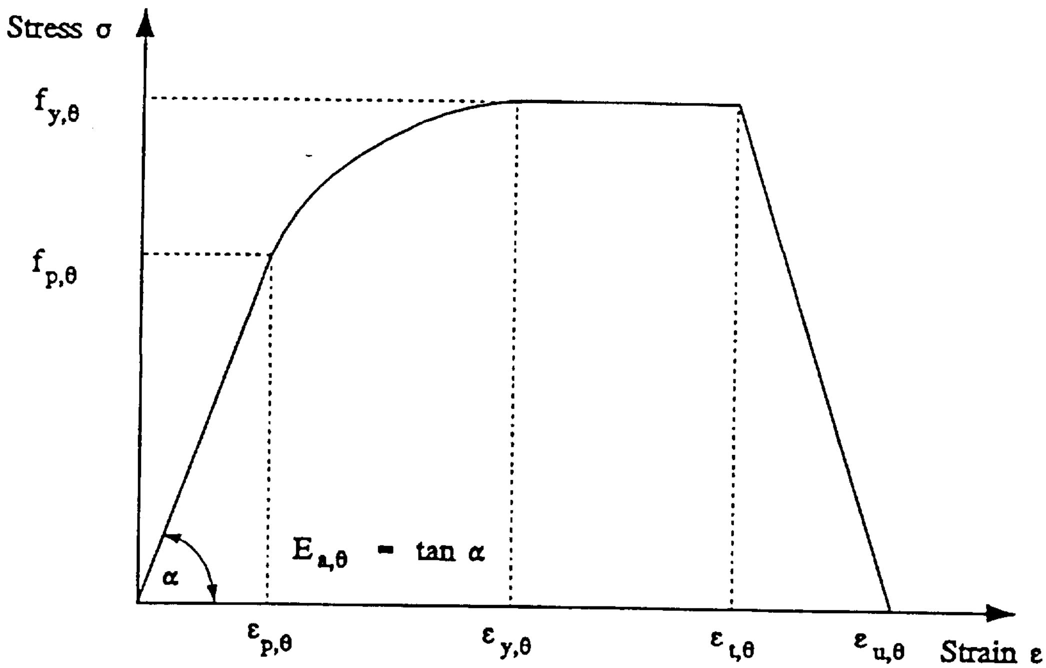
In terms of sophisticated and, it is presumed, more accurate thermal and structural analyses of fire performance, the computer programs called FASBUS-II (for structural analysis) and FIRES-T3 (for thermal analysis) were developed and have been used in the U.S. for calculating fire resistance. The original version of FASBUS-II was developed at the Illinois Institute of Technology more than thirty years ago and later by Wiss-Janney-Elstner and Associates (WJE) under an American Iron and Steel Institute (AISI) sponsorship. FASBUS-II is used by WJE in combination with the program FIRES-T3, which was developed originally at U.C. Berkeley [15]. The combined programs were used successfully by Jeanes [17] in simulations of experiments on a fire-exposed two-story frame structure. Such calculations have also been used by Skidmore Owings and Merril on a number of projects [18]. However, several users have reported numerical problems with FASBUS-II. It seems that FASBUS-II gives reasonably good values when a five second time interval is used, but, the solution does not converge for smaller time intervals [9,19]. This is an indication of a problem with the software.

A recent paper by Sullivan et al [15] has reviewed various numerical simulation computer programs for simulating the effects of fire on structures, including CEFFICOS (an earlier version of SAFIR) as well as FASBUS-II and FIRES-T3. They concluded that all of these programs have significant limitations, especially that they are not "user-friendly" and cannot be readily used by non-experts. However, certain programs have very useful capabilities and are being used extensively.

Among the best of the specialized computer programs is SAFIR, which was developed primarily by J-M. Franssen of the University of Liége in cooperation with ARBED [20,21]. SAFIR can simulate the thermal and structural response of fire-exposed structures. SAFIR is presently being further developed. With this in mind, it was decided to choose SAFIR for further evaluation.

Numerical simulation is more accepted in Europe than in the U.S. The European building code explicitly allows for numerical simulation as well as simple calculations for assessment of structural fire resistance. In "Eurocode-3: Design of Steel Structures" (EC3) a stress-strain curve is specified as a function of temperature, where the curve is linear up to the proportional limit, parabolic up to the effective yield strength, and then horizontal up to the limiting strain.

Stress-Strain Relationship for Steel at Elevated Temperatures



$f_{y,\theta}$	is	the effective yield strength;
$f_{p,\theta}$	is	the proportional limit;
$E_{a,\theta}$	is	the slope of the linear elastic range;
$\varepsilon_{p,\theta}$	is	the strain at the proportional limit;
$\varepsilon_{y,\theta}$	is	the yield strain;
$\varepsilon_{t,\theta}$	is	the limiting strain for yield strength;
$\varepsilon_{u,\theta}$	is	the ultimate strain.

Figure 2.3.1 [22]

EC3 prescribes a specific temperature relationship for such material properties as the effective yield strength, the proportional limit, and the reduction factor for the slope in the linear elastic range [22].

Reduction Factors for the Stress-Strain Relationship of Steel

at Elevated Temperatures

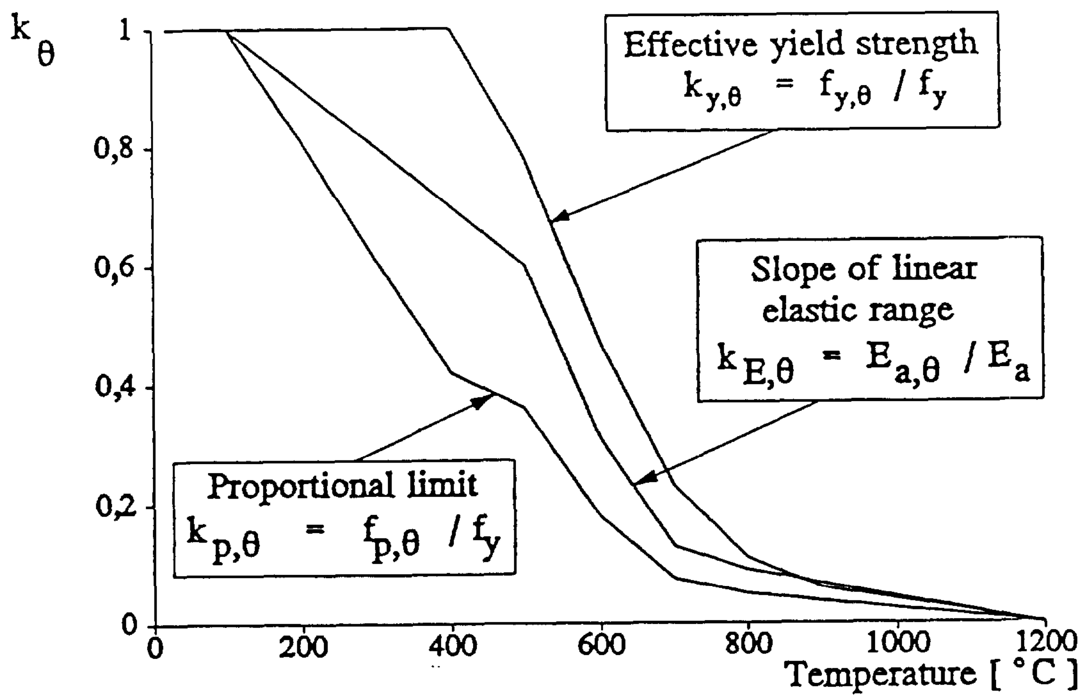


Figure 2.3.2 [22]

These two graphs are combined by the designer to create a stress-strain relationship for a specified grade of structural steel at any elevated temperature.

Stress-Strain Relationship with Temperature for 350 MPa Steel

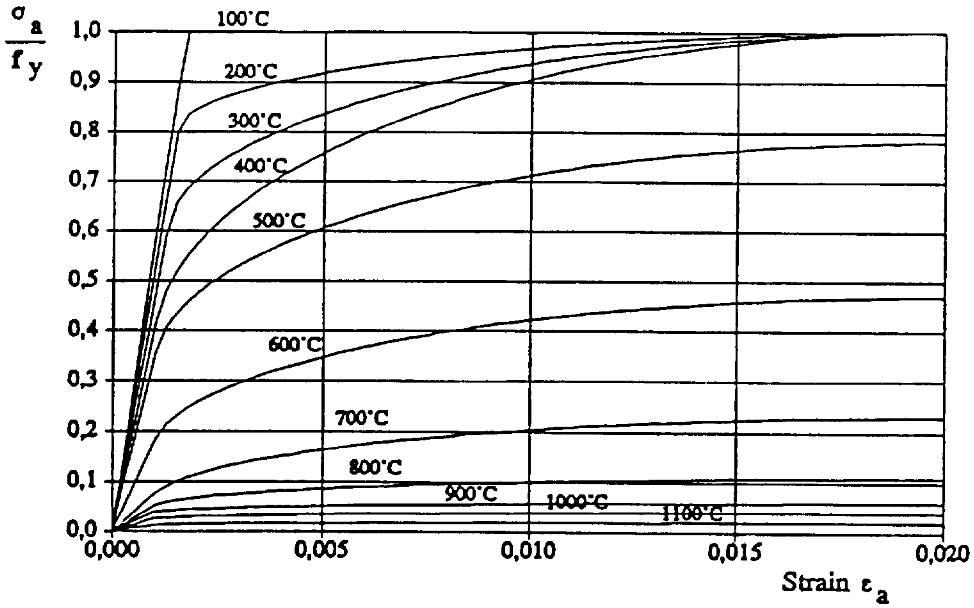


Figure 2.3.3 [22]

3.0 The SAFIR Finite-Element Software

The SAFIR software was developed in a VAX VMS environment but has been adapted by ATLSS to run on a SUN workstation and a Pentium PC. The ability to run on a PC should significantly enhance the appeal of the software.

The calculations performed by SAFIR can be primarily divided into two separate parts. The first is the calculation of transient and non-uniform temperature distribution of a structure subjected to fire. The second is the transient analysis of the mechanical behavior of a structure subjected to fire. The mechanical analysis uses output directly from the thermal calculation.

Simplified SAFIR Schematic

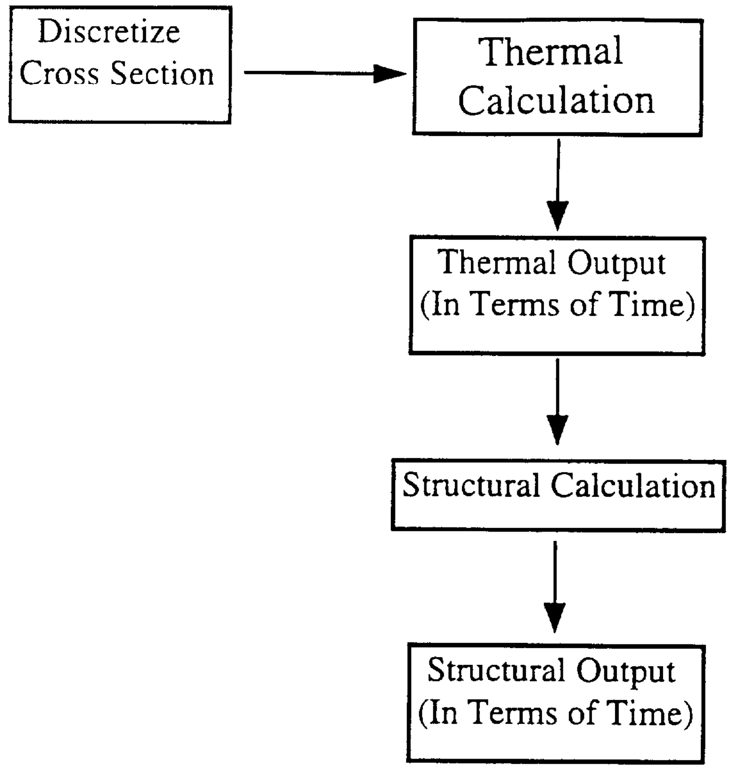


Figure 3.0.1

Nodes describing the elements for either thermal or structural calculations can be introduced in either a Cartesian or cylindrical system of axes. SAFIR has the ability to internally renumber the equations in order to reduce the band width of the matrix. Multi-point constraints (master-slave relationships) can be used to impose the same temperature or displacement at different nodes.

3.1 Transient and Non-Uniform Temperature Distribution

SAFIR has the ability to perform thermal calculations using three-dimensional (3-D) solid elements as well as two-dimensional (2-D) cross-sections. Solid elements are linear with eight nodes for typical bricks or six nodes for wedges. The material can be different from element to element, allowing the modeling of non-homogeneous structures. The cross-section of a beam element is described as a 2-D plane section, comprised of linear three-nodded triangular and/or four-nodded quadrilateral elements. A windows based post processor is available for the discretization of steel I-shaped sections. The material can be different from one element to another allowing the modeling of non-homogeneous cross-sections. Protected steel columns, reinforced concrete and many other types of composite sections can be idealized in 2-D for the thermal analysis.

SAFIR also has the ability to simulate the heat flux across hollow voids in structural sections, but, in order to preform this calculation the voids must be convex. Any node or set of nodes used to make up the section can have a temperature history imposed as a function of time. The user can define any piecewise-linear temperature history (or several other time functions) to any or all faces of a section.

The ISO standard temperature history may be specified as an option in SAFIR. Although the ISO temperature history is very similar to the prescribed ASTM-E119 temperature history (see Figure 2.1.3), the ASTM-E119 temperature history was also programmed as an option in the SAFIR code to facilitate use in the U.S.

SAFIR produces a file that lists the temperature of each element as a function of time, corresponding with the prescribed temperature-time history. The results from an example analysis are shown in Figure 3.1.1 below. Figure 3.1.1 shows the temperature history at the center of an unprotected solid steel bar subject to ASTM-E119 temperature-time history.

Temperature at Center of a Solid Steel Bar (30 cm X 30 cm)

Subjected to ASTM-E119 Standard Fire

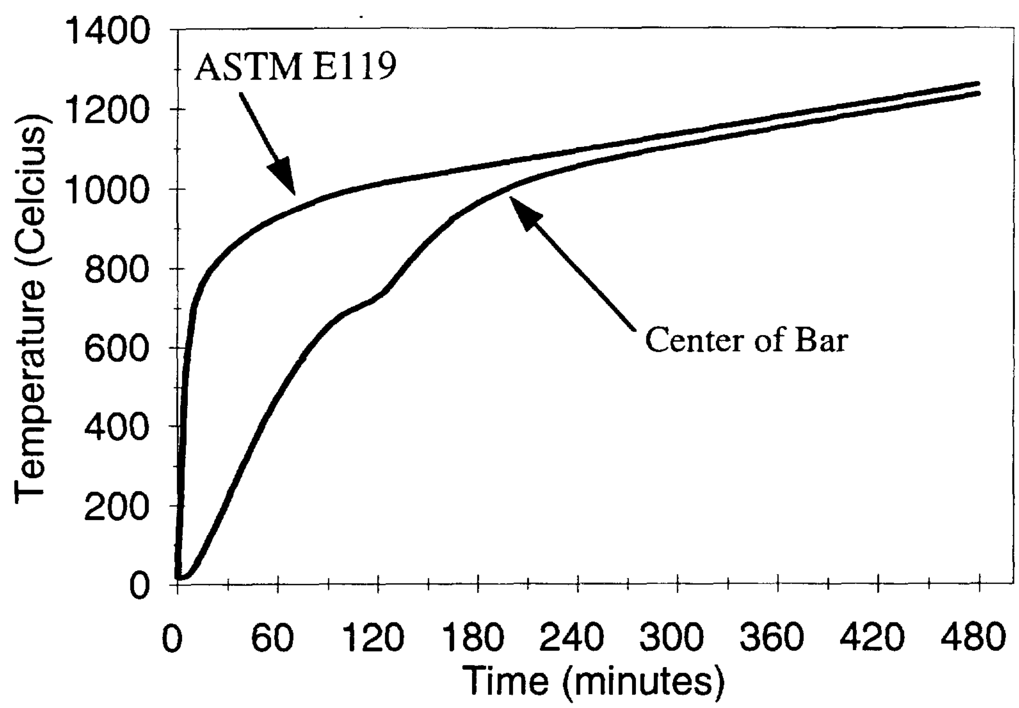


Figure 3.1.1

There is an irregularity in the temperature-time relationship in Figure 3.1.1 around 720°C. This temperature corresponds to the transformation of the steel from ferrite to austenite, and the irregularity in the curve reflects the latent heat of transformation.

SAFIR also has a good model for simulating the heat flux through concrete. ASTM-E119 requires that the water content of concrete is reported for a furnace test. SAFIR has the capability of taking the water content into account for thermal simulations. This calculation includes correction for moisture evaporation as the simulated concrete reaches elevated temperatures. In the Eurocode model for concrete, the water content has an influences the thermal calculations because the energy needed to evaporate the moisture is taken into account. SAFIR uses these Eurocode criteria to perform the thermal calculations. In this model water residing in an element evaporates at 100°C. Then the water may move to a cooler neighboring element and condense. This model does not take into account some of the factors effecting the movement of the water including the porosity of the concrete, preferential routes for moisture movement and effect of cracking on the structure.

Figure 3.1.2 shows thermal results from an example using concrete. Quarter symmetry was used with solid elements to model a concrete floor with a steel I-section passing through the center. The concrete floor and steel I-section are being exposed to a standard fire from beneath the floor.

Composite Floor Section Utilizing Quarter Symmetry

Fire Simulated from Beneath

Solid Elements

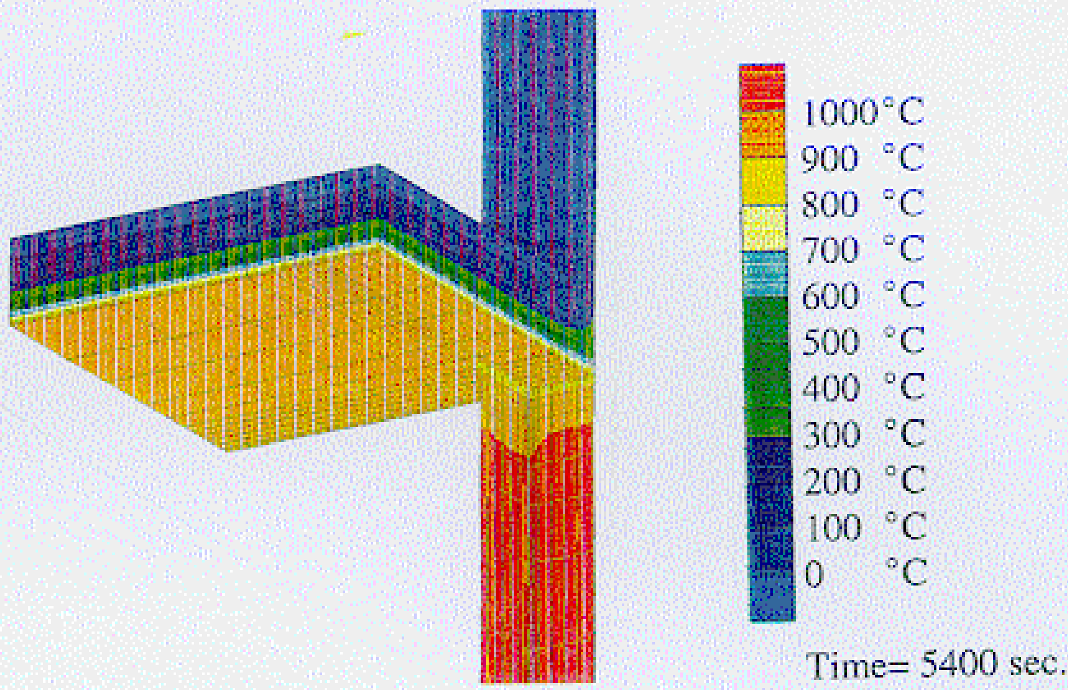


Figure 3.1.2

Below, is another example of a temperature distribution calculated by SAFIR. In this case, a prestressed concrete beam section is modeled. The prestressing bars are located in the lower region of the section, and do not have a significant effect on the temperature distribution.

Prestressed Composite Floor Section

Fire Simulated from Beneath

Plane Elements

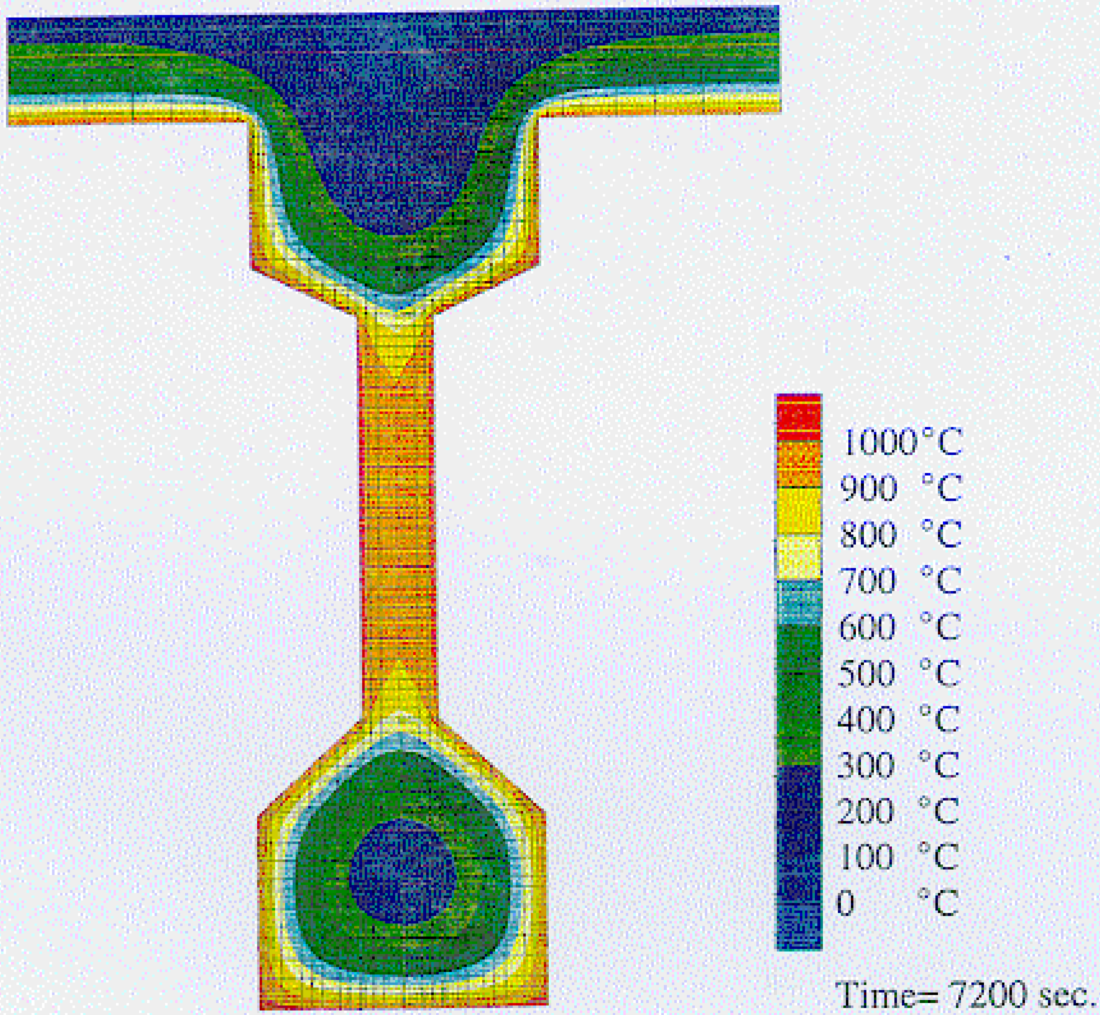


Figure 3.1.3

Once the thermal simulation of a cross-sectional plane is completed, the output file can be used to describe a beam element for simulation of mechanical behavior. The mechanical simulation is described in the next section.

3.2 Analysis of Mechanical Behavior

The transient analysis of the mechanical behavior of the structure uses the output file from the thermal simulation. The time steps used by the mechanical calculation correspond to the time steps defined in the thermal calculation.

In addition to solid elements, truss and beam elements are available in SAFIR, and 3-D frames can be modelled using these truss and beam elements. Truss elements are good for some simple cases, but the truss elements used by SAFIR can only be comprised of a single material. The truss elements also must have a uniform temperature. Simulations using solid elements are useful for many applications (Figure 3.1.2), but solid elements are not practical for analysis of the total structural response of large structures, therefore; the focus of this evaluation will be on beam elements.

The structure can be made up of beam elements for which the cross-section and temperature distribution have been defined from the thermal analysis. Calculations involving truss or beam elements can be made considering large or small displacements. The arc-length method (Rik's method) is used for the integration scheme to model partial unloading. The criteria used for failure in the mechanical calculations is when the stiffness matrix of the structure becomes negative, and convergence can not be obtained.

The user should be aware that SAFIR does not consider the effect of debonding, or shear failure. These types of failures should be assessed by appropriate independent calculations, if necessary.

3.2.1 Fiber Type Beam Elements

The beam elements used by SAFIR are comprised of a series of fibers, which represent each individual element of a cross-section described in the thermal calculation. Each fiber is given a centroid, an area, a defined material, and a temperature which varies as a function of time. The forces induced by load and thermal strains cause the fibers to expand and contract. The fibers can not separate from each other during the structural simulation, and plane sections are assumed to remain plane. Local buckling is not considered in beam element calculations.

3.2.2 Constitutive Models

The material properties of common structural steels and concrete are non-linearly temperature dependent. Some of the materials included in the code are models for Si and Ca based concrete, structural steel, prestressing steel, rebar, and some forms of insulation including gypsum board. The functional forms of these properties are given in the Eurocode and are programmed in the SAFIR code. The actual values of the functions are governed by several user-specified parameters. SAFIR can be modified to follow user-specified material models, but it is not set up to do this easily.

Only temperature-dependent elastic properties may be used for solid elements. Temperature-dependent elastoplastic properties may be specified for the truss and beam elements. The truss elements or each fiber of the beam are treated as uniaxial with respect to the material properties. With this simple uniaxial model, it is possible to determine whether the loading is tensile or compressive, and different properties may be used depending on the loading direction.

Unloading of elements is parallel to the loading elastic branch. The model will not allow for cracking of a material such as concrete. The concrete model used by SAFIR assumes that the tensile strength of concrete is zero.

3.2.3 Treatment of Residual Stress

SAFIR can be used to model the effects of residual stress simply by imposing a residual stress distribution before running the mechanical analysis. When the file is read by SAFIR for the structural calculation, any residual stresses or prestressing stresses specified are considered by means of initial strains. Where the total stress is:

$$\sigma = \sigma_i + \Delta_\sigma$$

Where:

σ = Total Stress
σ_i = Initial (i.e. residual) stress
Δ_σ = Variation of stress from the state of reference (i.e. from time = 0)

This equation cannot be used practically, because the material behavior is highly non-linear and the stresses cannot be added. It is better to write the material law in terms of strains, as shown below.

$$\varepsilon = \varepsilon_i + \varepsilon_{th} + \varepsilon_\sigma + \varepsilon_{cr}$$

Where:

ε = Real strain, linked to a field of displacements
ε_i = Initial strain
ε_{th} = Thermal strain (due to thermal elongation)
ε_σ = Strain from induced stresses
ε_{cr} = Creep strain

The fiber model, combined with this initial stress capability, make SAFIR ideal for modelling prestressed beams [23].

3.2.4 Sequence of Loading

All of the results of the structural calculation such as stresses, strains, deflection, internal forces, and support forces are given in terms of the evolution of time. This time corresponds to the original temperature-time history. The structural element can be loaded and then heated to failure, heated and then loaded to failure, or any combination of time dependent loading and heating can be simulated. It was found that the failure of the system was not dependent on the sequence of heating and loading.

3.2.5 Torsional stiffness and warping function

SAFIR has the ability to calculate the torsional stiffness and warping function of a section. There is no need to do this calculation unless the user intends to do a structural calculation which involves subjecting 3-D beam elements to significant torsion. The SAFIR beam element is not designed to simulate behaviors in which torsion is the design mode of failure, therefore; torsional failures must be checked separately. Torsional failure is not common in typical buildings.

3.2.6 Sensitivity to Numerical Parameters

Knowing that there has been some criticism regarding the ability of FIRES-T3 and FASBUS II to converge, a intensive study of the ability of SAFIR to converge was performed. These following parametric studies were made with pinned axially loaded columns. These pinned columns were chosen, because pinned axially loaded columns are the most sensitive to small changes in a system, therefore; they will provide an upper bound for the sensitivity of these following parametric studies.

There are three parameters that effect the time and accuracy of a calculation for a given case. They are the precision, time step sequence, and the minimum value of the time step that can be chosen in the backwards steps (Comeback).

The precision is the level of accuracy that is used in the matrix calculations. For most cases, a precision of 10^{-3} is adequate. Setting the precision as precise as 10^{-12} will make the calculation considerably more accurate, but this accuracy comes at the cost of longer computing time. For instance a simulation on a column made at 10^{-12} precision can take 20% longer than the same calculation made at 10^{-3} precision. Calculations made using several different time steps, and different values of comeback, had a maximum variation of 0.06% using 10^{-3} precision, whereas, the maximum variation recorded using 10^{-12} precision was only 0.00006%.

The time step parameter can be set so that the increment of time is synonymous with the increment of load. A study was performed to see how the chosen time steps for a given case would effect the final solution. The precision was set to 10^{-6} and the comeback was set to 0.1. An isothermal column was heated, then loaded to failure. The values of the time step were set to be equivalent to the load steps. Several different load steps were chosen, ranging from 100 N to 1000 N. The maximum variation recorded for this case study was also only 0.06%.

The results showed that SAFIR was able to converge to an acceptable accuracy regardless of what the user chooses for the initial time step. Running the same experiment with the precision set to 10^{-12} showed a maximum variation of only 0.00006%.

When the chosen incremental load step exceeds the capacity of the structure, SAFIR automatically chooses smaller increments. The user must also choose a minimum value for this time increment. This parameter is called the comeback. If the user chooses a small increment for this parameter (0.001) it makes very little difference what is chosen for the original increments. The comeback should be set to a value less than or equal to the final time step. The comeback has a significant effect on the final solution. Using +/- 5 % of the limit load of the structure is an acceptable criteria for the comeback in structural calculations.

3.3 Pre & Post-Processing

A simple windows based pre-processor for the discretization of steel I-sections for direct input into SAFIR was recently developed at University of Liége. The required input includes the name of the section, the number of nodes, which sides of the section will be subjected to fire, and which temperature-time history they wish to prescribe.

The code can be adapted to give results in a format compatible with commercial graphic software, but, it is currently programed to present the results in a format that can be readily used by a graphical post processor developed at the University of Liége. The post processor can be used to show temperature distributions, deflections, stresses, strains, and different materials used in composite sections.

4.0 Application of SAFIR

4.1 Comparisons with Other Codes for Simulation of Structural Elements Exposed to Fire

In 1994 a paper was written by Jean-Marc Franssen on the comparison of five computer based computational methods. The five commercial programs compared were CEFICOSS, DIANA, LENAS, SISMEF, AND SAFIR. Some of the main differences between these software are listed in the table below:

Comparison of Five Computer Based Fire Codes

	CEFICOSS	DIANA	LENAS-MT	SAFIR	SISMEF
Thermal Analysis	2D	3D	*1	3D	*1
Formulation	Finite Difference	Finite Element	-	Finite Element	-
Structural Analysis	2D	3D	3D	3D	2D
Beam Formulation	Bernoulli	Mindlin	Bernoulli	Bernoulli	Bernoulli
Nodes	2	3	2	3	2
DOF per node	3 - 3	6 - 6 - 6	7 - 7	7 - 1 - 7	3 - 3
Sectional Discretization	Rectangular Fibers	Gauss - Simpson	Rectangular Fibers	Triang. or Quadr. Fibers	Rectangular Fibers
Longitudinal Integration	Gauss	Gauss	Linear between the nodes	Gauss	Gauss
Large Displacements	Updated Lagrangian	Total Lagrangian	Updated Lagrangian	Total Corrotational	Updated Lagrangian
Residual Stresses	Initial Strains	Initial Stresses	Initial Strains	Initial Strains	Initial Strains
Material Law	Uni-Axial	Multi-Axial *2	Multi-Axial *2	Uni-Axial	Uni-Axial

*1 Thermal results are taken from TASEF, written by Wickstrom
*2 Von Mises yield-criterion and isotropic strain hardening

Figure 4.1.1 [24]

Each of the five computer programs were used to simulate the static behavior of eight different assemblies subjected to fire loads. All of the codes used the same stress vs. strain & temperature relationships as prescribed by Eurocode 3. SAFIR compared reasonably well with the other methods. Below is a typical example showing the results from these numerical simulations.

Eccentrically Loaded Column Subjected to ISO Fire

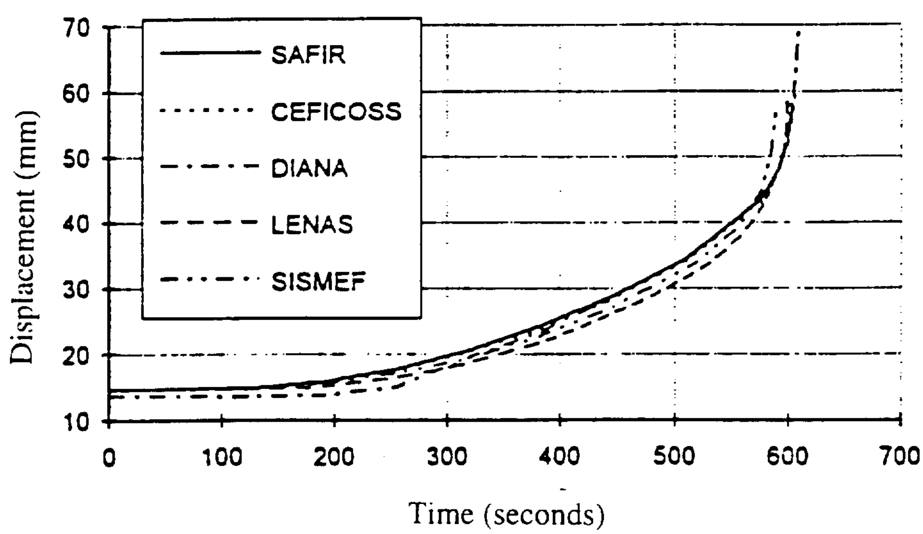


Figure 4.1.2 [24]

More significant variation occurred in the cases of axially loaded columns. But, even in these cases the maximum variation was less than 6 %. It seems that the main factor for this variation could be due to the way that the codes simulate the effect of residual stress [24]. For instance, DIANA models the residual stresses in the structural calculation as initial stresses, which are kept constant during the simulation until they exceed the maximum allowable stress prescribed by the Eurocode 3 for a given temperature. But, SAFIR along with the other three codes model the residual stresses as initial strains. The initial strains remain constant during the mechanical simulation [23]. Eccentrically loaded columns are not very sensitive to residual stress. Therefore, these differences would have less effect on the variability among results for eccentrically loaded columns. It should be noted that even though there was some variability among the different programs, it was not anywhere as great as the variability observed in actual test data.

4.2 Comparisons to ABAQUS

Jean-Marc Franssen's paper compares several different codes that are specialized for the simulation of assemblies subjected to extreme heat. It is also useful to compare the results to an accepted commercial finite-element code. ABAQUS was chosen for this comparison.

The main difference between the analyses performed with SAFIR and ABAQUS is the way that the beam elements are discretized. ABAQUS does not have the fiber-element approach for beam elements. Although ABAQUS does have provisions for reinforcing bars in an otherwise homogeneous cross-section, it is not as flexible as SAFIR for beams with composite cross-sections. Also, ABAQUS beam elements can have only a linear temperature gradient across the cross-section, whereas the temperature can vary in an arbitrary way with the SAFIR fiber-model approach [25,26].

4.2.1 Usability

Although ABAQUS has many different cross-section types that can used as beam elements, it does not allow for the modeling of non-homogeneous sections such as concrete filled tubes or steel sections encased in concrete. In order to simulate these types of sections in ABAQUS, the user must discretize the sections as solid elements. This discretization would be acceptable for the simulation of one member in a furnace test, but, it is impractical for modeling entire structures. Furthermore, ABAQUS beam elements can not be used to model the behavior of a shape subjected to non-uniform heating scenarios. In order to model a section with a non-isothermal temperature distribution, solid elements would also be required. [25,26]

4.2.2 Accuracy

Several cases of column capacity were simulated using both SAFIR and ABAQUS. Since it is impossible to model a non-isothermal solution as a beam element using ABAQUS, isothermal sections were used for the comparison. SAFIR uses the stress-strain-temperature curve prescribed by EC3. In order to compare the two codes the stress-strain distribution for each temperature as prescribed by EC3 was entered into the ABAQUS input file separately. A typical comparison between the two codes is shown below.

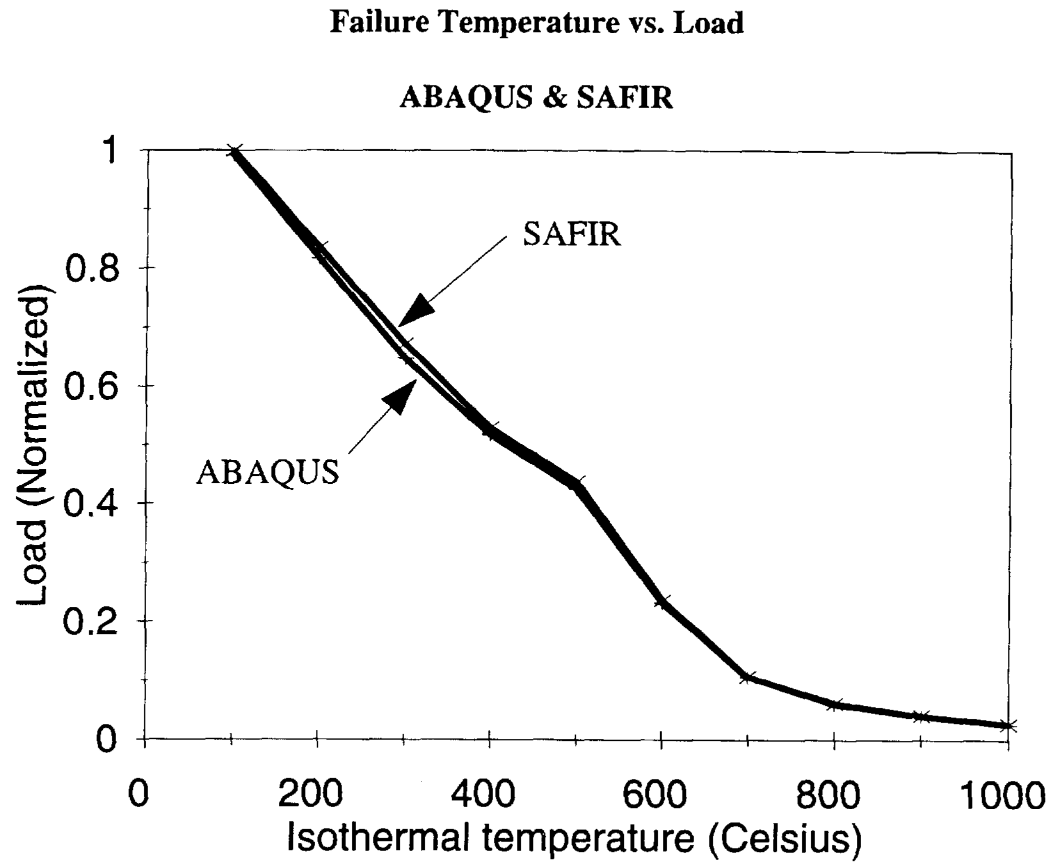


Figure 4.2.2.1

The two loading simulations are identical for each of the two codes, except for the type of beam elements as discussed above. The values calculated by ABAQUS were slightly, but consistently lower than those calculated by SAFIR. This may be due to the fact that the beam element used by ABAQUS to simulate an I-section does not include fillets between the web and flanges. The beam element used by SAFIR, is composed of fibers and allows the user to account for the fillets at the intersection of the web and flanges.

Fillets at Intersection of Web and Flanges

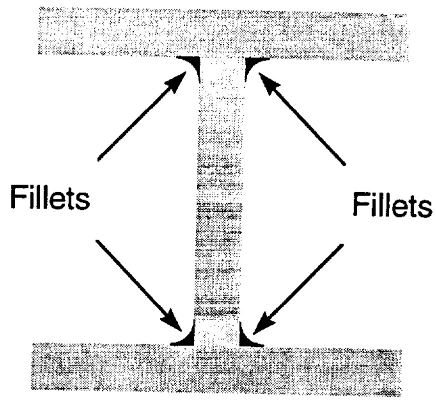


Figure 4.2.2.2

These fillets only make up 1.3 % of the whole section, but, the difference they make in the final solution is also around 1.0 %. This is a significant contribution to the variation in the graph above, which has a maximum variation of only 3.8 %.

4.3 Comparisons to Experimental Data

In order to further verify the usability/accuracy of SAFIR, data have been collected from several different test facilities around the world. As mentioned earlier, it was observed that there was considerable variation in the data for like structural members, under the same fire and structural loads. These variations occurred even when the columns were tested at the same facilities. These variations are due to a variety of reasons described earlier in the chapter 2.0.

4.3.1 Comparisons to Tests on Steel Columns

Test data have been collected from many different laboratories in several countries around the world. The most regular data was that of the HEA-100 columns tested in Rennes, France. These European columns have the following dimensions:

European Section HEA-100

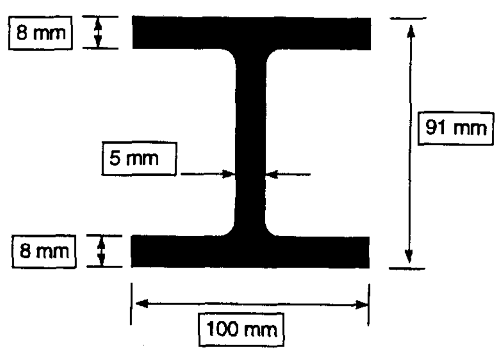


Figure 4.3.1.1

The following case studies are from column tests in which the column was supported so that it would fail in the weak bending axis. Initial calculations with SAFIR fell right in the middle of the test data. If appropriate safety factors were applied to the SAFIR calculation, all of the test data would have fallen safely above the predicted values.

According to AISC the permissible out-of-straightness allowable in the weak axis (sweep) for this section is equal to the length divided by 480. For these simulations, the length of the columns was 1994 mm so the maximum allowable sweep was 4.1 mm.

Sweep, According to AISC

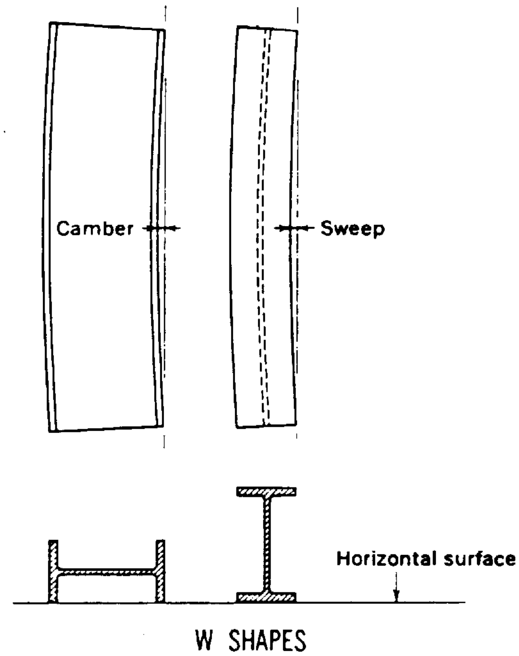


Figure 4.3.1.2 [27]

In order to evaluate out-of-straightness, the column tests were simulated using two bounding assumptions about the out-of-straightness:

CASE #1 - Column without end restraints with initial eccentricity of L/480

CASE #2 - Column without end restraints with no initial eccentricity (i.e. Perfectly Straight)

Several simulations at different load levels were run for each case. In these simulations, the load was kept constant and the column was subjected to the standard fire, until the column failed. The figure below shows the predicted load vs. temperature relationships for the two cases and compares the results with the experimental test data.

Actual Test Data & SAFIR Simulation

Load vs. Temperature

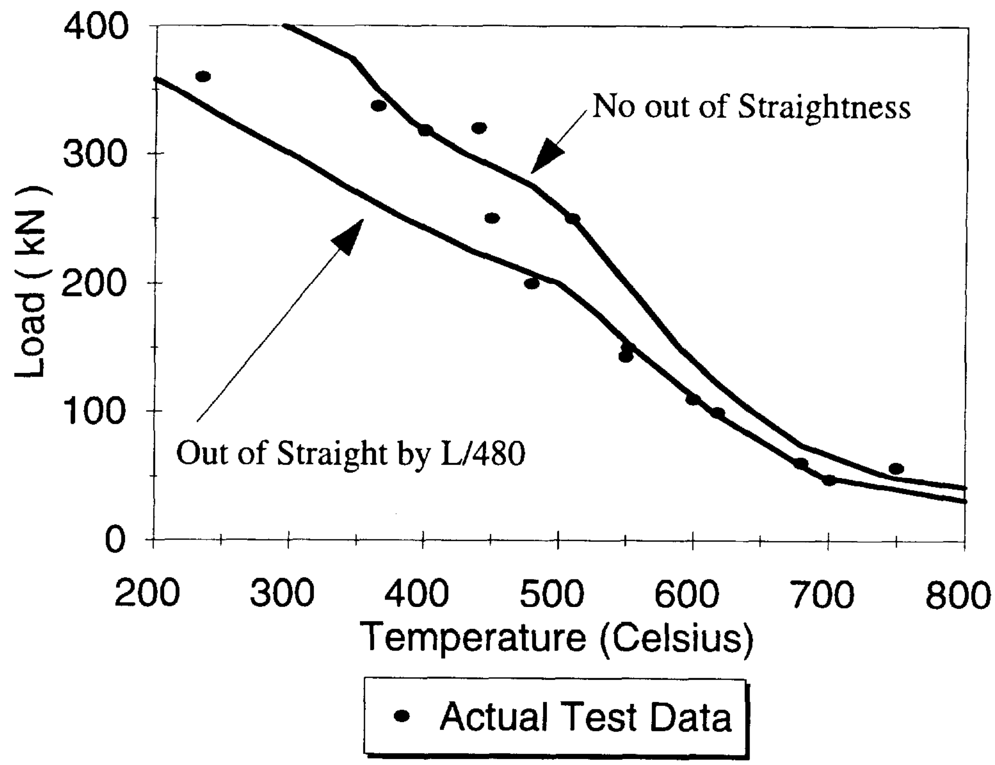


Figure 4.3.1.3

Most of the test data fell within the bounds of these two cases; however, a few test data fell outside of these bounds.

There are several reasons that can be used to explain why test data exceeded the

SAFIR simulation for a perfectly straight column. The empirical model for the yield strength, ultimate strength, and the modulus of elasticity as prescribed by EC3 is based on mean values from material tests at elevated temperatures [22]. The yield strength of the steel was documented as 300 MPa for all of the members, but, the actual strength of the steel could have had considerable variability.

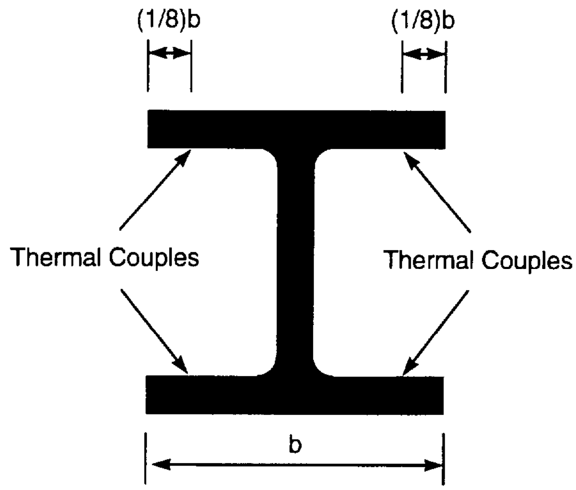
Also, EC3 assumes the steel to be perfectly plastic with no strain hardening up to 400°C. The effects of strain hardening become more pronounced at higher temperatures, but the EC3 model does not allow for modeling of strain hardening above the yield strength of the steel (see Figure 2.3.3). Any strain hardening would also increase the apparent strength.

Another factor is the heat lost through the end fixtures, which can cause the test specimen to act stiffer than predicted by computer simulated models. In addition, actual end conditions in a structural test are never completely free of rotational resistance. This slightly stiffer condition can cause experimental loads to be significantly higher than expected, especially with the case of a pinned column.

There are also a few reasons that can be used to explain actual test loads that fell below the load vs. temperature plot for the case with maximum out-of-straightness. The initial eccentricities of the HEA-100 specimens were not recorded. The test specimens may have had sweep values greater than the AISC limits. Other variations in the steel section can lead to lower than expected test values. Flanges out of square anywhere along the length of the column can lead to local buckling before the predicted load is reached. Although the effect of residual stresses diminishes at higher temperatures, very high residual stresses could lead to lower failure loads near ambient temperatures. The steel finite element discretization is based on the average steel dimensions typical for that shape. Small variations in the cross-sectional area can also lead to significant variations in test results.

Finally, ASTM-E119 specifies that the temperature recorded from an actual column furnace test is the arithmetic mean of no less than four thermocouples placed on the outside surface of the section in a manner that will most accurately represent the temperature of the section. However, ASTM-E119 does not suggest where these measurements should be taken. According to the SAFIR simulations, the surface temperature of an HEA-100 section can vary up to 29.1 °C. It is not apparent from the test data exactly where the temperatures of the HEA-100 sections were measured. Some of the literature indicates that the 1/8 points of the flange are a good location to represent the temperature of the section [28]. The temperatures taken from SAFIR to compare to the test data were the average of the points shown below:

Points Where Temperature has been Measured to Calculate the Average Temperature of a Simulated with SAFIR



NOTE: Due to symmetry all of these points were exactly the same temperature.

Figure 4.3.1.4

The variation in the experimental data makes it impossible to accurately evaluate the safety level of the structural column, without several tests to determine the scatter for a particular assembly. ASTM-E119 only requires that one test be performed. It can be very costly to produce enough experimental data to get a good idea of what the scatter is for a particular case.

It can be seen that, due to a large variability in the actual test data, the agreement between actual test values and predicted values will not always be so good. It should be noted that if the actual test data have such a significant scatter, that a reasonable level of acceptance should be established, based on the scatter of the test data. In addition, a safety factor should be established, based on cross-section and material for example, that will bring the actual used value to an acceptable level of safety.

4.3.2 Comparisons to Tests on Concrete Filled Tubes

The concrete-filled tube (CFT) is a popular method of construction in Asia and is gaining in popularity in the U.S. One of the advantages of CFT is that the concrete provides a significant heat-sink and the steel, therefore; requires minimal or no insulation. Preliminary studies of CFTs have been performed. Furnace test data on CFTs have been acquired from the National Research Council (NRC) in Canada [7,29]. One of the problems with CFTs is the wide range of possible concrete strength properties and the wide variety of tubes makes a large number of possible combinations that would have to be fire tested to prove that these sections can be used without fire protection. The cost of this testing may be prohibitive and could preclude the introduction of an efficient method of construction in the U.S. Analyses with SAFIR, supplemented by some test data, could reduce the need for extensive fire testing of every combination of CFT.

The following comparisons are with actual tests performed at NRC in Canada. The dimensions of the CFT cross-section are as follows:

Concrete Filled Tube Dimensions

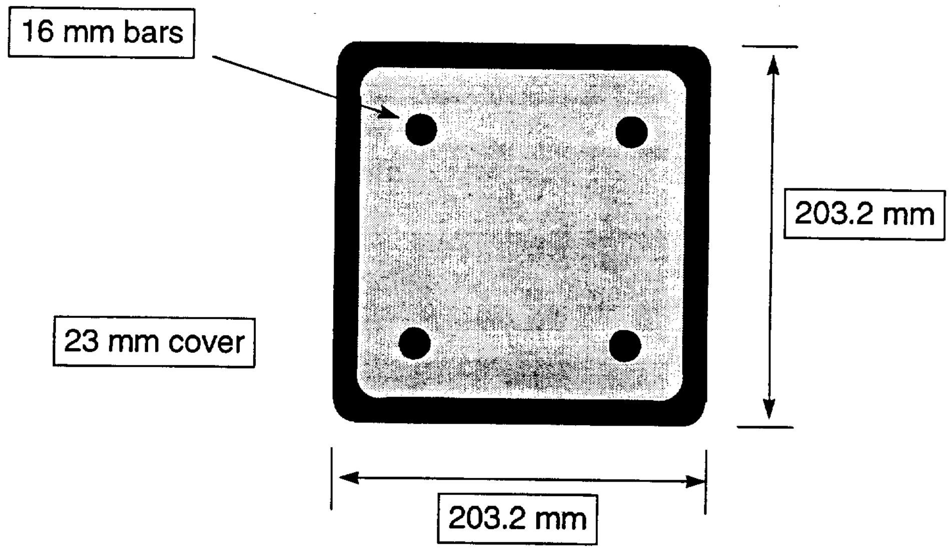


Figure 4.3.2.1

The simulated and actual test data shown below shows that, if a CFT is exposed to fire, the column first expands quickly to a peak, then drops quickly after about 25 minutes.

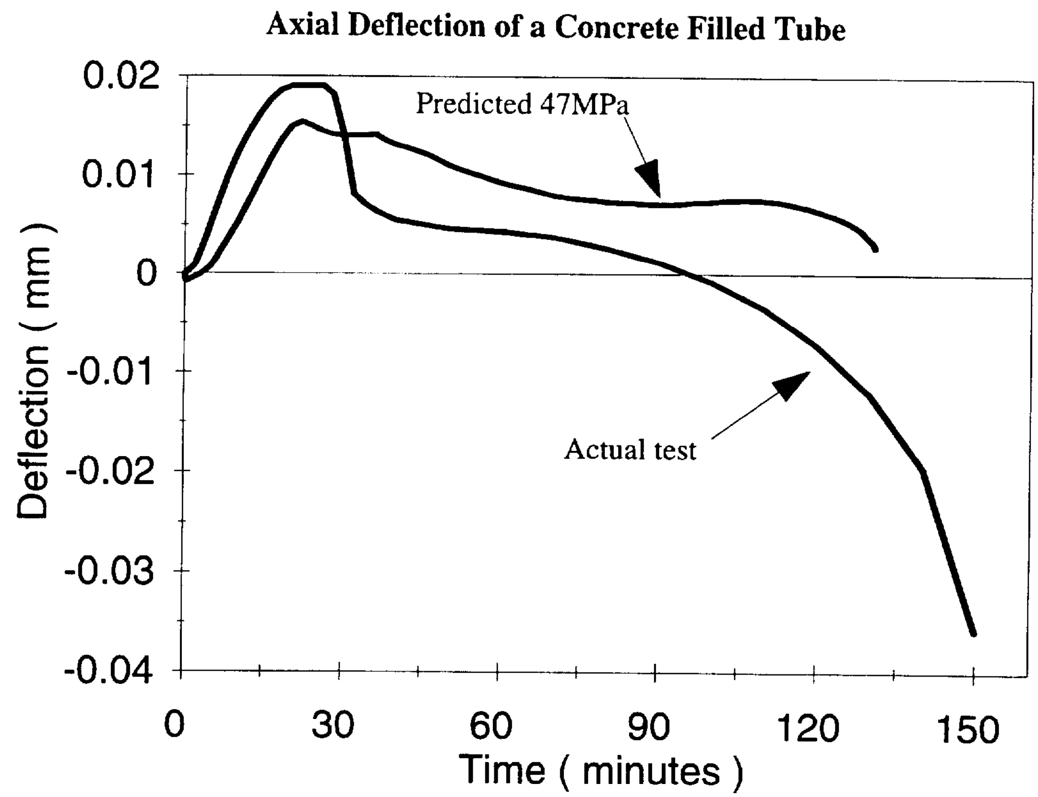


Figure 4.3.2.2

Accurate finite element modeling of loaded CFTs exposed to fire is extremely difficult, for several reasons. When the steel is first exposed to the fire it will expand both longitudinally and circumferentially. The axial expansion of the steel will cause the concrete to debond, crack, or some combination of the two. The circumferential expansion of steel will further assist in the debonding of the concrete and possibly cause spalling to occur. The cracking, spalling, and debonding that occurs does not necessarily cause a CFT to fail. The concrete still remains contained within the steel tube.

At the beginning of the tests, the steel elongates and begins to take a disproportionate share of the load. As the steel expands, the concrete is put into tension and may crack and leave horizontal gaps. The steel tube is unsupported next to these gaps, and the steel often develops a local buckle at these locations (See figure 2.1.2). Such behavior is evident in Figure 4.3.2.2 where the sudden decrease in axial displacement occurs. Beam elements used by SAFIR and other finite element codes cannot model this complex behavior.

When the expansion of the steel and the decrease in the yield point of the steel finally cause yielding and/or local buckling of the steel, the concrete becomes engaged. Eventually, failure of the concrete also occurs. In the SAFIR simulation the CFT is modeled as a beam element, which does not consider the effects of local buckling. Therefore, the simulated steel yields slowly and the concrete gradually takes on the load. In fact, in the simulation plotted in Figure 4.3.2.2, the concrete is not fully engaged until 85 minutes into the simulation.

In the case of an axial load, a CFT can have significant strength and stiffness beyond the cracking/pulverization of the concrete. However, the material properties become very different at this point. Even the most sophisticated concrete models have a difficult time predicting the behavior of CFTs even at ambient temperatures [30,31].

At room temperature, a confined concrete column can withstand far more load than that of an unconfined section. This confinement can raise the effective strength of the concrete to be several times to several times the unconfined measured values. This confinement is not effective, however, at the elevated temperatures produced by the ASTM-E119 test. The steel can become so soft that its confining strength is close to zero.

There is another significant phenomena that occurs when a CFT is exposed to extreme temperatures. That is the water which is released from the concrete at elevated temperatures. This water not only assists in the debonding of the concrete, but, it is very significant in absorbing heat from the fire, and cooling the section. SAFIR's beam element does not account for the debonding of the steel and concrete, and although SAFIR does model the effect of water within the concrete, it does not consider the moisture that gets trapped between the steel and the concrete in the CFT. It is for this reason that the temperatures calculated by SAFIR for this section are significantly hotter than those measured in the later part of the actual furnace test.

Temperature at the center of a CFT subjected to the

ASTM-E119 Fire

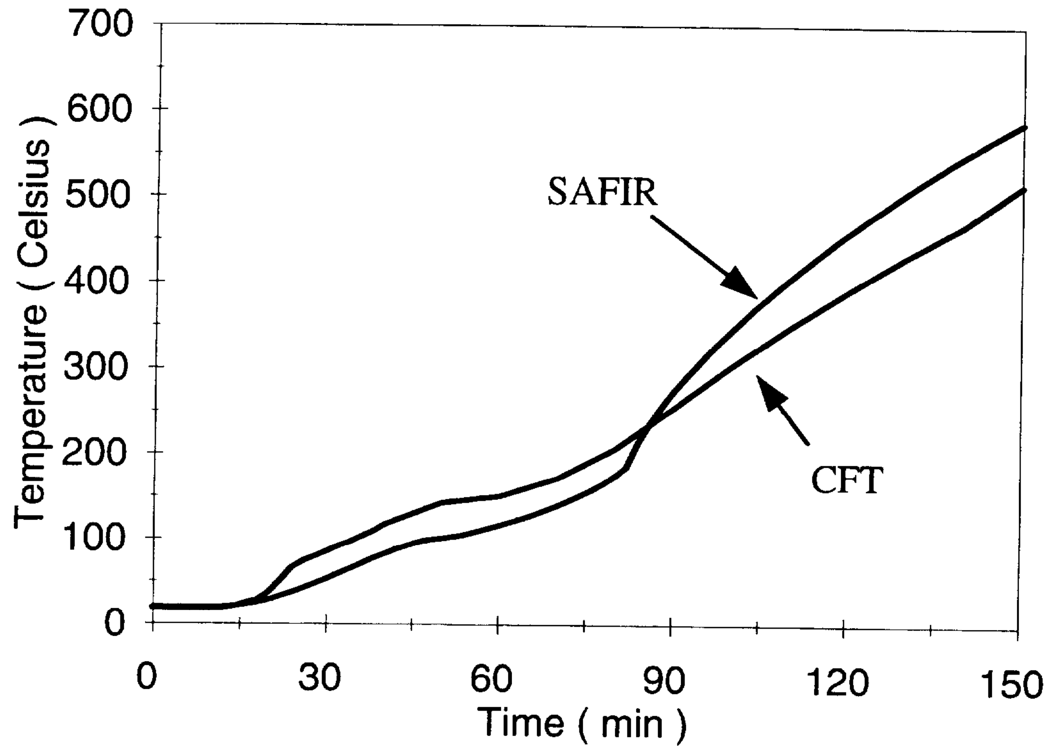


Figure 4.3.2.3

4.4 Residual Stress

Residual stress does not have a significant influence on the load bearing capacity of a steel member in bending. But, it does have a significant effect on the load bearing capacity of axially-loaded columns in compression. Extensive measurements of residual stress were made at Lehigh in the 1970's. Figure 4.4.1 shows a typical residual stress distribution in a rolled shape.

Typical Residual Stress Distribution

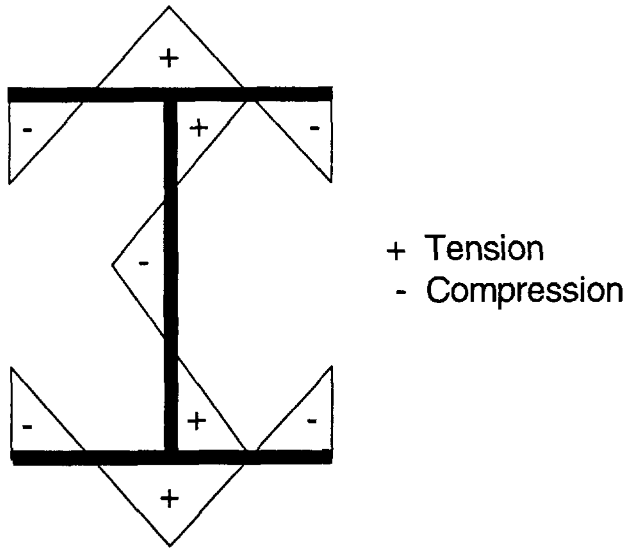


Figure 4.4.1

These residual stress measurements were collected and organized. Figure 4.4.2 shows a distribution of the absolute value of the peaks in the measured residual stress distributions for rolled sections. The mean value of the peaks in the residual stress distribution in rolled steel I-sections is about 25% of the minimum specified yield strength (MSYS) of the steel. Some residual stresses were reported to be as high as 150% of the MSYS, however.

Peak Residual Stresses Found as a Percentage

of the Yield Stress

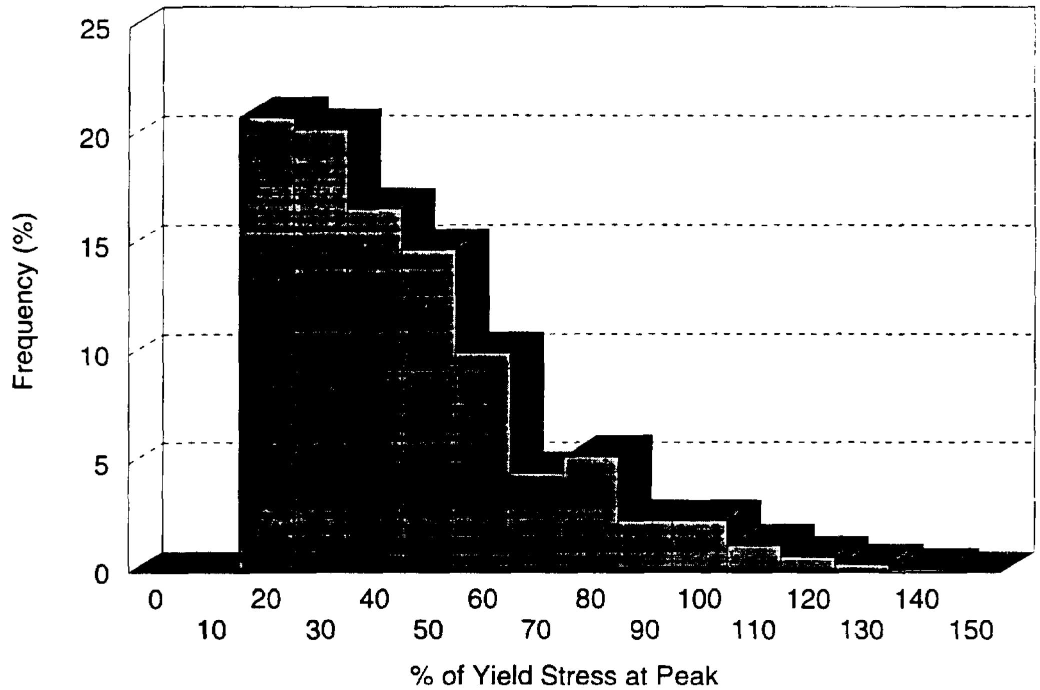


Figure 4.4.2

Calculations were performed to determine the effect residual stress has on the strength of a an axially loaded column. The results of these calculations are shown below.

Normalized Peak Load as a Function of Percentage of

Peak Residual Stress

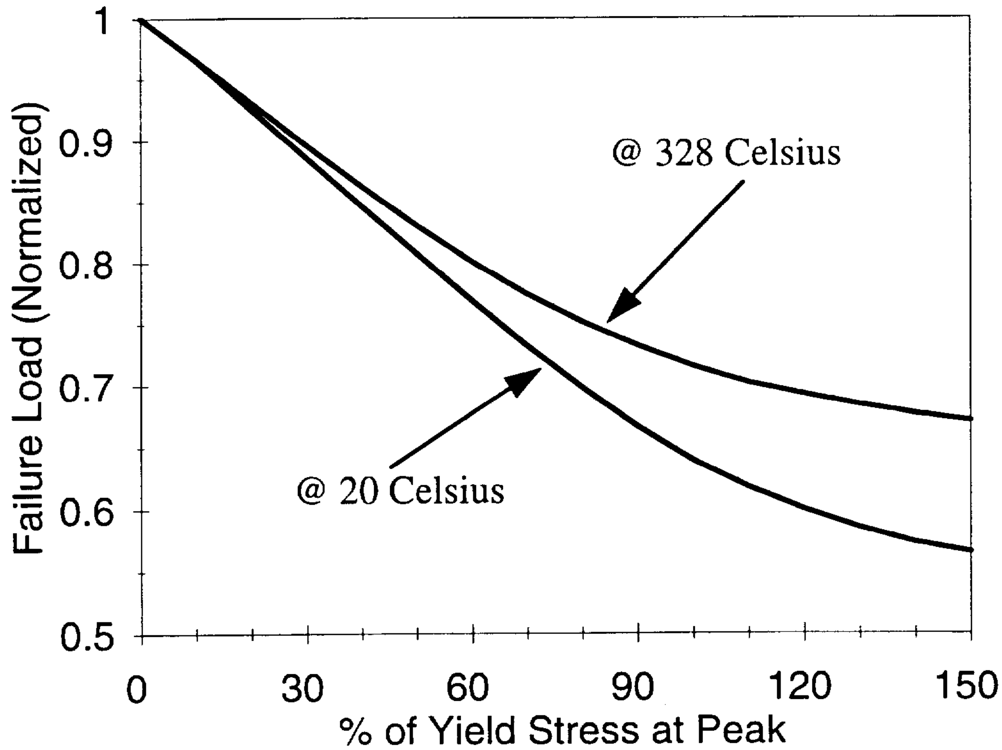


Figure 4.4.3

Residual stresses can reduce the load bearing capacity of a column by about 30%. Also shown in Figure 4.4.3, is that residual stress has less effect at elevated temperatures.

4.5 Slenderness

Calculations were performed using SAFIR to investigate the response of a few different slenderness ratios. The load in these simulations was about the maximum design load, i.e. 60% of the capacity, Pn computed in accord with the AISC LRFD code [27]. The result of these simulations for a W14X311 are shown below.

Average Temperature of a W14X311 Pinned Column

Heated According to ASTM-E119

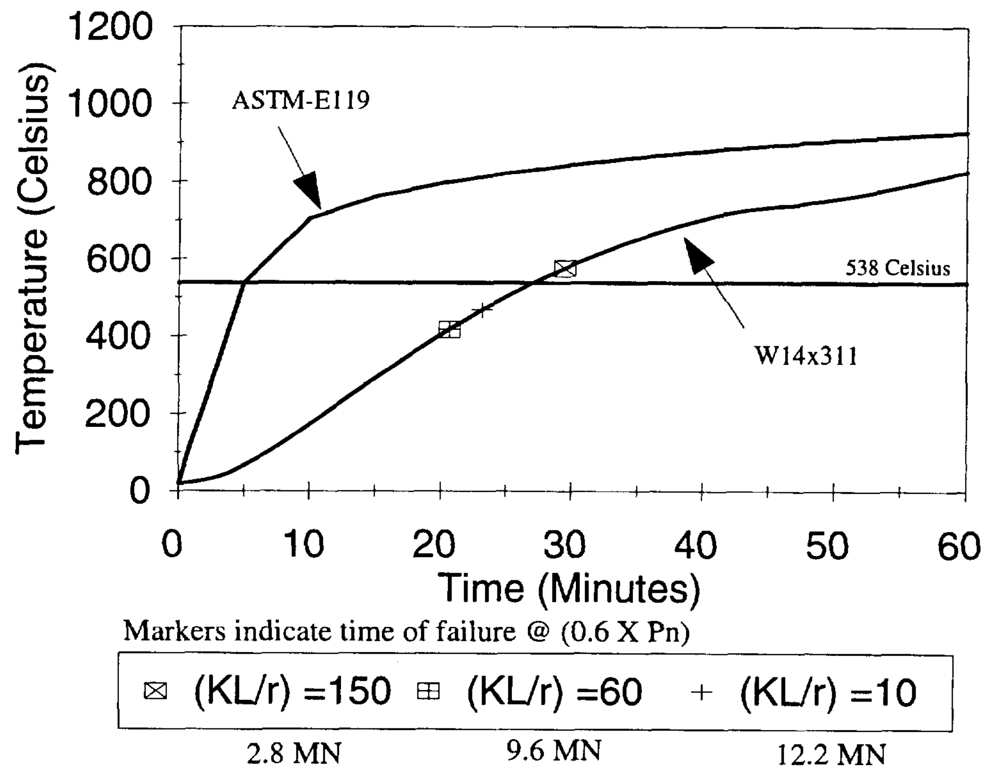


Figure 4.5.1

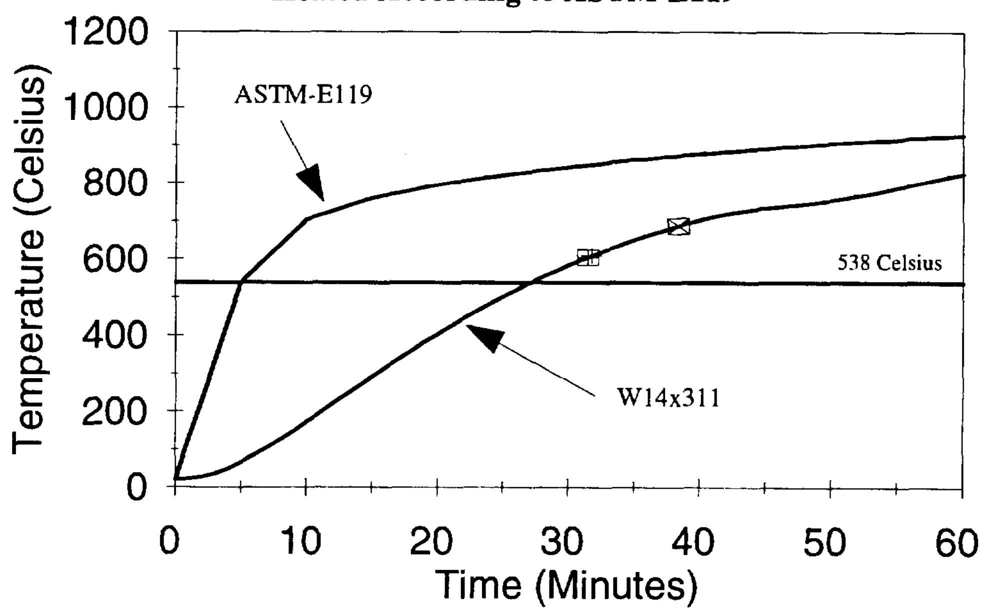
There is a line drawn at 538°C. This would be the failure time as prescribed by ASTM-E119. It is not surprising to see that these columns are predicted to fail around 538°C. However, it was surprising to see that in some cases the temperature criteria was unconservative. The difference in time between the simulated failure of the section with

(KL/r)= 60, and the limiting temperature of 538°C was less than ten minutes, but this simulation was run for a bare steel column. If this column had enough insulation to achieve a two hour rating by the temperature criteria, than the difference between the two failure times would be three times longer. In other words, a column with a two hour fire rating by the temperature criteria, could fail in as little as an hour and a half.

Generally columns in buildings are not loaded to their design load. This is because the building columns are typically designed to limit displacement produced by wind loads. Figure 4.5.2 shows the results of similar simulations to those in Figure 4.5.1, except the load in this case is half of the typical design load or about 30% of Pn.

Average Temperature of a W14X311 Pinned Column

Heated According to ASTM-E119



Markers indicate time of failure @ 0.5 X (0.6 X Pn)

⊠ (KL/r) =150	⊞ (KL/r) =60	+ (KL/r) =10
1.4 MN	4.8 MN	6.1 MN

Figure 4.5.2

At half the design load, the simulated columns lasted longer than 538 °C, but, the longest lasting column still only lasted 40 minutes. Other simulations showed that W14X311 columns loaded to only 10% of the design load (6% of Pn) still failed in less than an hour. It is surprising that the magnitude of the axial load does not make a more significant difference in the time to failure.

4.6 Application to a Continuous Structure

The structural responses of the individual elements are dependent on their end constraints, which: 1) are strongly coupled to the response of the overall structure; and, 2) can have a major impact on element load-bearing capability. Without a frame-type analysis, end constraints of the various structural elements that comprise a real structure are unknown. In particular, such constraints are generally not similar for similar-looking elements, not "simple," and not constant in time. It is clear that computational thermal and structural analyses can provide a means of addressing and resolving these latter issues.

Most furnace test data for columns are for single columns, simply because it is too expensive to furnace test whole structural assemblies. A designer uses these tests to prescribe the amount of fire proofing required for a given section. But, the accuracy of this method is extemely inconsistent. In a typical building the redundant qualities of the beams making up the structure give it far more endurance than would be predicted by tests on single members [32]. An analysis of the frame in Figure 4.6.1 was conducted to demonstrate the effect of continuity of the structure.

Five Bay Continuous Structure Subjected to

ASTM-E119 Fire

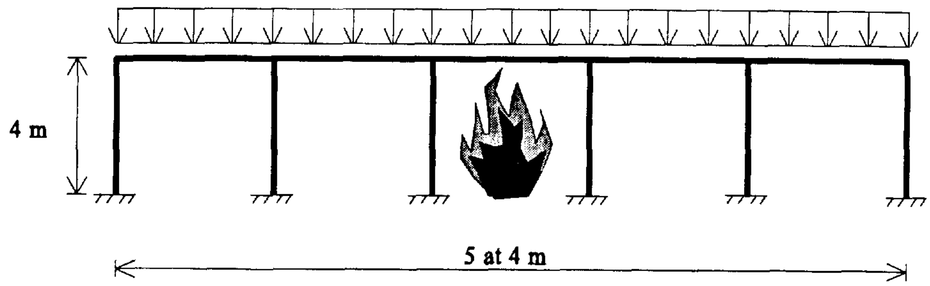


Figure 4.6.1

First, a no-load furnace test was simulated on the unprotected beams and columns. These calculations indicated that the critical temperature, 538 °C, was reached in the column in 11.5 minutes, and in the beam in 13.3 minutes. Then, a simulation of a loaded ASTM-E119 furnace test was conducted. In this case, the column collapsed in 12.4 minutes.

Finally SAFIR was used to simulate the response of the entire structure to an ASTM-E119 fire in the center bay. This frame has a distributed load on the beams over all five bays. The magnitude of this load is such that the beams are at 0.6 times the critical load, and the interior columns are at 0.4 times the critical load. An ASTM-E119 temperature history is prescribed for all the surfaces of elements facing into the center bay. In this frame simulation, the structure lasted 34.8 minutes before collapse.

Although the difference between the loaded and unloaded option was small, the over all structure lasted 300% longer than predicted by the current standard. This example shows the over conservative nature of fire rating structures based on the limiting temperature criteria or loaded option of individual structural elements.

4.7 Summary of SAFIR

Results of the study show that SAFIR seems to be the best software available for the simulation of fire effects in structures. It is easy to use and agrees well with experimental data. Comparisons to other numerically based codes show good agreement.

Case studies were performed that verified the accuracy of SAFIR. For example, the buckling capacity of steel columns at specific temperatures was computed using SAFIR as well as the commercial finite-element software ABAQUS. The two computed results were in good agreement with each other and were also in reasonable agreement with fire test data.

Case studies also demonstrated the usefulness of the special-purpose SAFIR software. For example, SAFIR was used to model composite cross-sections including CFTs. SAFIR, with its "fiber model" approach, is ideal for these types of problems. Most commercial finite-element packages do not have this fiber-model feature, therefore; it is difficult to model composite cross-sections using beam elements. The usefulness of SAFIR was also demonstrated by showing the advantages of a computer simulation in evaluating special situations. For example, a simple model of the behavior of a five bay

2-D steel frame subjected to a fire in the center bay was run to demonstrate that the collapse load was greater than would be expected for a uniformly heated section such as in a standard furnace test.

It is clear that it is much more efficient to evaluate these special situations, and special composite cross-sections with a computational tool in lieu of fire testing. It is very expensive to individually qualify every new cross-section or configuration that a designer may want to consider. It is for this reason that many new and possibly better designs will never get past the drawing table. The exception of a numerically based code, such as SAFIR will make the simulation of new designs reasonably inexpensive, and address a long-term goal of efficient, economical, and innovative building construction.

5.0 Hand Calculation

There is a simple procedure for calculating the design axial load of a column for flexural buckling given by AISC, in the Load and Resistance Factor Design (LRFD) manual [27]. This procedure is as follows:

Design Compressive Strength According to LRFD

$$\text{Design Load} = P_n = \Phi_c \, A_g \, F_{cr}$$

where:
P_n = Applied load
Φ_c = 0.85 (Safety Factor)
A_g = Gross Area
F_{cr} = Critical Force per unit area

The formula for F_{cr} depends on the value of λ_c:

$$\lambda_c = \left[\left(\frac{K \cdot L}{r}\right) \cdot \frac{1}{\pi} \cdot \sqrt{\frac{Fy}{E}}\right]$$

where:
K = Effictive Length Factor
L = Unbraced Length
r = Radius of Gyration
Fy = Yield Stress
E = Modulus of Elasticity

If $\lambda_c \le 1.5$:

$$F_{cr} = 0.658^{\left[(\lambda_c)^2\right]} \cdot Fy$$

If $\lambda_c > 1.5$:

$$F_{cr} = \frac{0.877}{(\lambda_c)^2} \cdot Fy$$

By simply varying the material properties as a function of temperature, as is done in Australian building code, a simple hand calculation for axial capacity can be produced. See the substitutions below:

Modified LRFD Equations

$$\text{Design Load} = P_n = \Phi_c \ A_g \ F_{cr}(T)$$

where: P_n = Applied load

Φ_c = 0.85 (Safety Factor)

A_g = Gross Area

$F_{cr}(T)$ = Critical Force per unit area

The formula for F_{cr} depends on the value of $\lambda_c(T)$:

$$\lambda_c(T) = \left[\left(\frac{K \cdot L}{r}\right) \cdot \frac{1}{\pi} \cdot \sqrt{\frac{Fy(T)}{E(T)}}\right]$$

where: K = Effictive Length Factor

L = Unbraced Length

r = Radius of Gyration

E(T) = Yield Stress

Fy(T) = Modulus of Elasticity

If $\lambda_c(T) \leq 1.5$:

$$F_{cr}(T) = 0.658^{\left[\left[\lambda_c(T)\right]^2\right]} \cdot Fy(T)$$

If $\lambda_c(T) > 1.5$:

$$F_{cr}(T) = \frac{0.877}{\left[\lambda_c(T)\right]^2} \cdot Fy(T)$$

This modified LRFD procedure was performed for several different temperatures and compared to the same data that was used in the SAFIR comparison, in order to produce the following results:

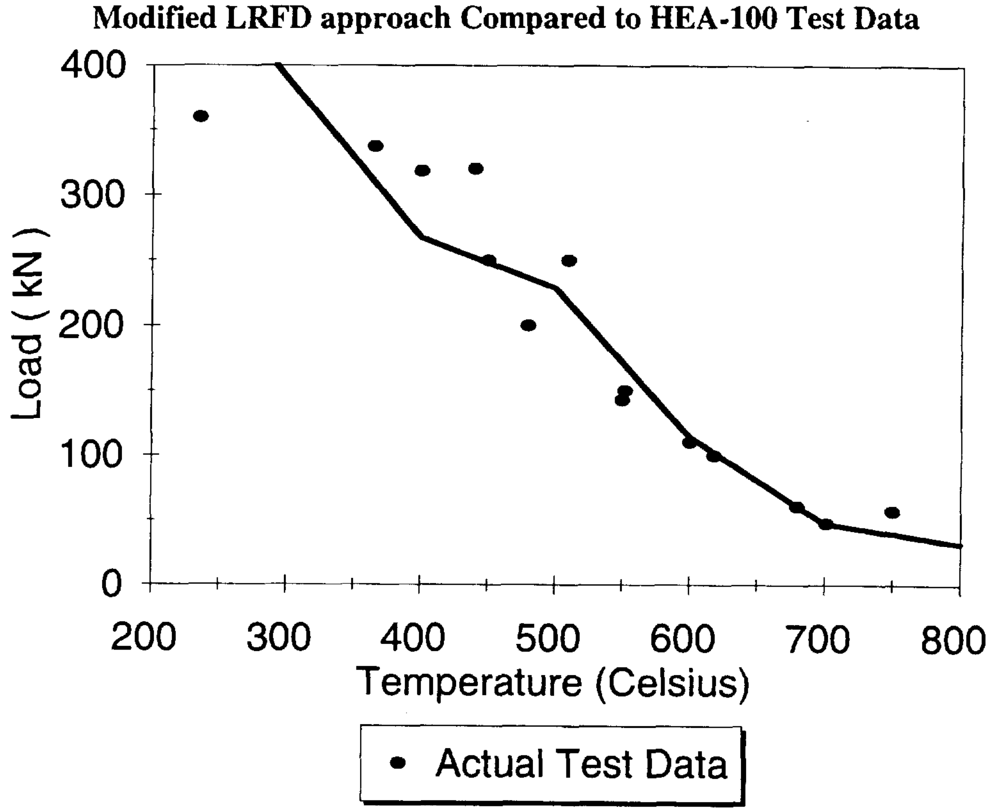


Figure 5.0.1

This simplified modification of the design strength formulas for flexural buckling prescribed in LRFD shows a good lower bound for this sampling of data.

In this calculation, the yield strength, and modules of elasticity vary with the same empirical model that is prescribed by EC3, and used by SAFIR.

Note that at temperatures above 500 deg. Cel., all of the actual test data, and all of the computational predictions converge to the yield load for a given temperature:

$$Fy = \sigma_y(T) \text{ X } A$$

Where:

Fy	= Yield load
$\sigma_y(T)$	= Yield stress, as a function of temperature
A	= Area

The simple hand calculation shown above is good for predicting lower bounds for simple cases such as isothermal steel columns. But, for more complex cases such as continuous frames, a more powerful numerical method must be used.

6.0 General Discussion

The test method ASTM-E119 was first published by ASTM as C19 in 1918. A number of refinements have been made in the standard since that time. However, several provisions, including the temperature-time curve, the major apparatus and the acceptance criteria have remained essentially unchanged [5].

Results depend on factors such as the type of assembly and materials being tested, the characteristics of the furnace, the type and level of the applied load, the nature of the boundary conditions, and details of the workmanship during assembly [5]. By using a computer based analysis an engineer can produce repeatable results that can be given an appropriate safety margin, so that an acceptable level of safety can be established.

It is not intended to imply that ASTM-E119 furnace testing is not needed. The full-scale ASTM-E119 loaded test data from the past and future must be used to define this safety margin for given materials and configurations [13]. However, alternative methods should be available.

Several advances have been made in the understanding of material behavior under severe temperatures since the first version of ASTM-E119 was published. It is clear that with the technology available today several other options should be considered. Computer based modeling can be used to explore a large variety of ideas that could be very difficult and/or very costly to explore using the current testing standards.

There are several different types of fire resistant materials available today, and more are constantly being developed. It is very expensive to test or retest structural assemblies with these new materials. If a computer method could be accepted, the developers of these materials would have a chance to market their products after limited furnace tests followed by suitable analytical studies. Once the fire resistant properties of the material have been established in actual fire tests, the material properties can be used in computer simulations on a large number of cases.

The typical fire resistant material that is used today is a spray on material, which offers no structural stiffness. Even if the insulating material has some structural stiffness (e.g. concrete), current design codes do not allow this material to be used as part of the load carrying capability of the structural element. A computer simulation, combined with limited testing, could be used to demonstrate the added load capacity provided by stiff insulating materials.

On a similar note, when an engineering firm is designing a structure, they often pick their construction details from a list of structural members and joints that have already been pre-qualified with certain types of fire resistance [33]. It is very costly and time consuming to actually test new configurations. Therefore, the designers are limiting themselves to these prequailfied details. This kind of limitation would be unnecessary if the designers were allowed to use the current technology available to simulate new and more interesting designs and configurations.

SAFIR simulations indicate that the current ASTM-E119 temperature criteria is not conservative for all cases. In fact, in some cases, simulations indicate that it is 25%

unconservative. This is compensated for by the fact that the prescribed temperature history is so severe.

SAFIR is a potential solution to these limitations of the present approach. Using computational methods to understand the effects of fire on structures would lead to more accurate prediction criteria. With more accurate prediction methods, it is not necessary to be so conservative with the qualifying criteria.

Even though all of the parameters of separate furnace tests may be alike. The results from a series of separate tests will always have significant scatter. It is important that tests from different times and places are comparable. The acceptance of standard computer simulation methods would lead to more consistent fire ratings.

Simple calculations were shown to be relatively accurate for some simple cases. For example, the buckling load of steel columns at high temperature was calculated using the design equations from the AISC code, modified to take into account the effect of temperature on the material properties. Values of the yield strength and modulus of elasticity at the temperature of interest were substituted for the ambient temperature values that are normally used in these equations. These modified equations gave reasonably good agreement with fire test data. However, for more complicated cases such as composite cross-sections or non-isothermal temperature distributions, more complicated finite-element codes are required.

A major anticipated result of the proposed research is the identification of a practical and reliable computation-based alternative to the ASTM-E119 furnace test method for determining ASTM-E119 standard fire resistance ratings. Acceptance of such a computational alternative would lead to significant savings in the cost of determining building-code-specified fire resistance ratings. With relative ease and with relatively little cost, computational-based ratings would be used to test out feasibility of exploratory building design concepts relative to safe fire performance. The designer would not have to depend solely on cumbersome and expensive furnace tests to determine acceptability of designs. The situation would lead to more efficient, economical, and innovative building construction, including use of advanced construction materials, and increased fire safety.

7.0 Conclusions and Recommendations

A full range of possible alternative computational methods for fire rating structural elements has been evaluated, from simple calculations to sophisticated numerical simulation. Sophisticated numerical simulations include commercial finite-element packages as well as the specialized computer program SAFIR, developed by J-M. Franssen of the University of Liége. The authors traveled to Liége where they acquired and received training for SAFIR. The software was then adapted to run on a Sun workstation and on a Pentium P.C. at Lehigh University.

7.1 Conclusions

1. The preliminary results indicate that it may be feasible to consider the computational approach as an alternative to ASTM-E119 furnace testing. One advantage of the computational alternative is that the results would be more consistent than furnace testing, which produces scatter up to 30% for steel members and up to 40% for concrete members.

2. Simple calculations were shown to be relatively accurate for some simple cases. For example, the buckling load of steel columns at high temperature was calculated using the design equations from the AISC code. Values of the yield strength and modulus of elasticity at the temperature of interest were substituted for the ambient temperature values that are normally used in these equations. These modified equations gave

reasonably good agreement with fire test data. However, simple calculations cannot be used for composite cross-sections, or non-isothermal temperature distributions.

3. The results of this evaluation show that SAFIR is the best software available for the simulation of fire effects in structures. It is easy to use and the built-in database of material properties and prescribed temperature histories are very useful. It is useful for evaluating the fire resistance of all common types of construction. The fiber model for beam elements has many advantages over conventional beam elements, including the ability to model residual stress and prestressing, composite cross-sections, and non-isothermal temperature distributions.

4. Case studies verified the accuracy of SAFIR. For example, the buckling capacity of steel columns at specific temperatures was computed using SAFIR as well as the commercial finite-element software ABAQUS. The two computed results were in good agreement with each other and were also in reasonable agreement with fire test data.

5. Case studies also demonstrated the usefulness of the special-purpose SAFIR software. For example, SAFIR was used to model composite cross-sections including concrete-filled tubes (CFT). SAFIR, with its "fiber model" approach, is ideal for these types of problems. Most commercial finite-element packages do not have this fiber-model feature, therefore it is difficult to model composite cross-sections using beam elements.

With commercial finite-element software, three-dimensional solid elements can be used to model this type of cross-section, but it is impractical to model significant structural frameworks using solid elements.

6. The failure of a column or other structural elements is highly dependent on the end restraints. SAFIR simulations show that the time to failure of a column in a continuous frame was more than three times longer than predicted from furnace testing. This is among the numerous reasons that the ASTM-E119 rating procedure is believed to be excessively conservative.

7. It is clear that it is much more efficient to evaluate special situations and special composite cross-sections with a computational tool in lieu of fire testing. It is very expensive to individually qualify each of these cross-sections or situations in fire tests. Many more cases can be simulated with a computational tool than can be tested. Innovative structures can be easily evaluated with a computational tool.

7.2 Recommendations

Additional research should be performed to evaluate computational approaches for fire rating structural elements. This additional research will help to instill confidence in the U.S. building-code-making and -using community that a calculation-based ASTM

E119-type method of determining fire resistance is a reliable alternative to the recognized ASTM-E119 furnace test method. The following tasks are recommended:

1: Further development of SAFIR

A number of enhancements were identified that could facilitate the use of SAFIR and increase the usefulness of the results. Among these are a graphical user interface, a means of writing selected results into a separate file for further processing with other software, and enhanced graphics for the output.

2: Analyses of Fire-Resistant Steel

One of the recommendations from the Workshop on High-Performance Materials in Fire held in Chicago on 18 May 1996 was "Characterizing and developing new high-performance steels for fire". One major barrier to the acceptance of such steel in the U.S. is that the current fire rating method is based on the attainment of a temperature rather than the load-carrying capacity at that temperature [1,34]. Calculations with the SAFIR computer software are an excellent method of demonstrating the improved fire resistance of steel with improved high-temperature stress-strain properties in a fire.

3: Analyses of Prestressed Concrete Members

There are indications from researchers in Europe that prestressed concrete members may be unconservatively designed for fire resistance. In particular, the gradient in thermal expansion of the members from the exterior to the interior may cause loss of prestress forces and associated loss of load-carrying capacity long before the prestressing steel begins to reach high temperatures. SAFIR should be used to simulate the behavior of prestressed concrete members to investigate this potential failure mode.

4: Further Evaluation of the Effects of Continuous Structures

Larger assemblies, including some 3-D structures with fire scenarios in individual rooms should be analyzed.

5: Simulations with Real Fire Scenarios

There is an extraordinary large amount of data that suggests that the ASTM-E119 temperature history is too severe. Simulations should be performed using more realistic fire temperature histories.

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A range of computational methods were evaluated for predicting the load capacity of structures subjected to fire. Results were compared to furnace experiments on loaded steel columns and concrete filled tubes. Simple calculations are accurate for simple cases such as steel columns at uniform temperature. Special-purpose finite-element software, SAFIR, was also accurate for members with nonuniform temperature distributions and/or composite cross-sections. SAFIR simulations of a continuous frame showed that it withstood three times the fire-exposure duration predicted from column furnace testing. Computational methods could serve as an alternative to the furnace test method for determining fire resistance ratings.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)
fire ratings; fire resistance rating; furnaces; load capacity; steel columns; structural members, structural systems

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